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The
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Digitalisation of Legacy Machine Tools

Aiden J Lockwood, Gavin Hill, Matei Moldoveanu,
Rikki Coles, Rab Scott.

CATAPULT
High Value Manufacturing

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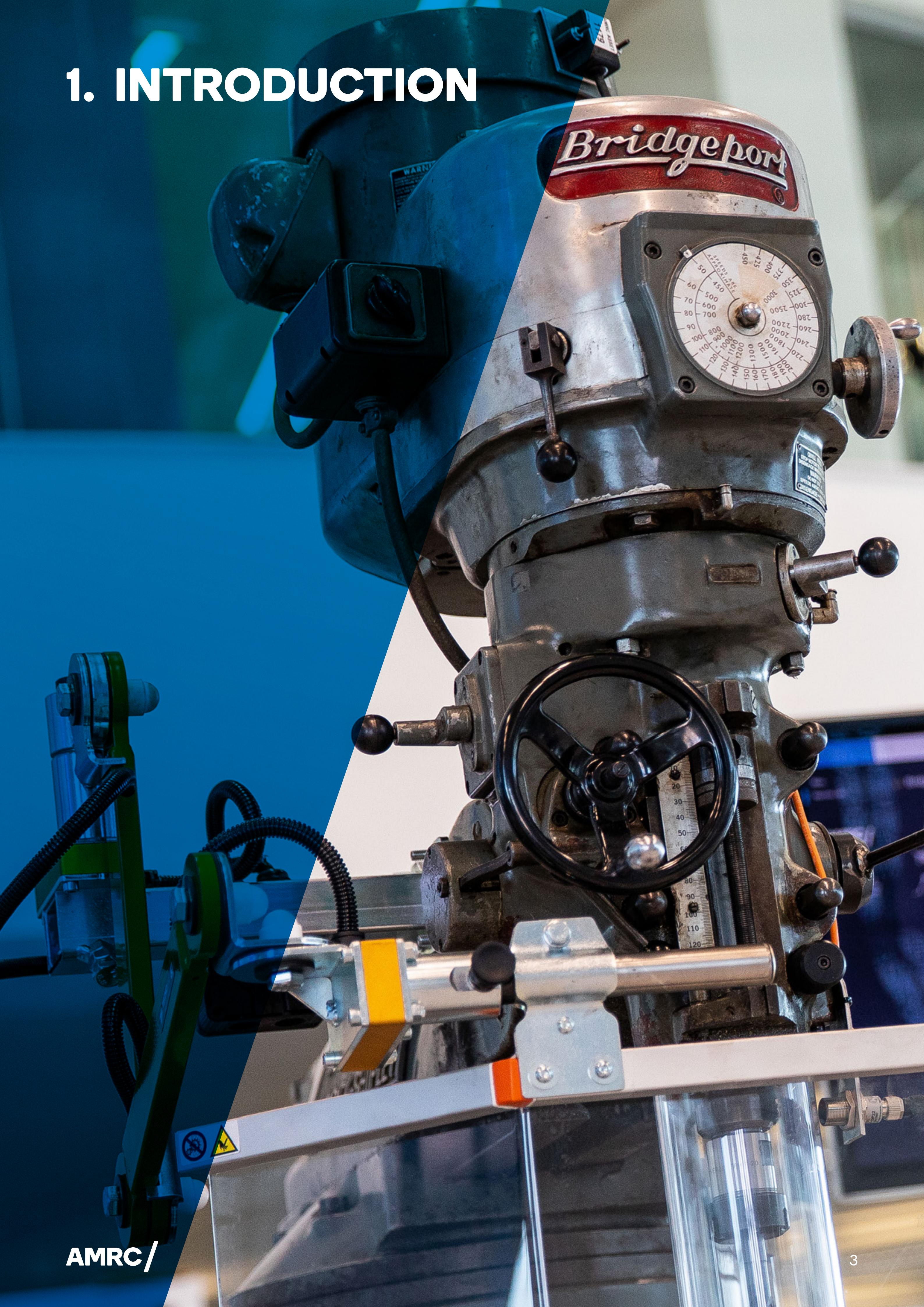
Abstract

As Industrie 4.0 or the 4th Industrial Revolution (4IR) gains momentum, the main adopters remain the large manufacturing primes/OEMs. One reason for this is that the small to medium sized enterprises (SMEs) within the supply chain believe digitalisation is not within their reach, mainly due to perceived cost and lack of available "digital" skills within their businesses. The Advanced Manufacturing Research Centre (AMRC) has demonstrated that digitalisation of legacy machines in this example, is accessible to the SME community through simple and low-cost sensing and cloud technologies. Initially, for only a few hundred pounds, it is possible to enable 4IR readiness of any type of machine, irrespective of age, where the AMRC demonstrate the connectivity of both a 1956 Colchester Bantam lathe, as well as a 1980's Bridgeport Turret Mill with increased capability.

1. INTRODUCTION



I. INTRODUCTION

Digital technologies are transforming the manufacturing industry. A report in 2017[1] identified digitalisation as a $100 trillion opportunity for both industry and society through adoption of these technologies[2]. In line with this technology surge comes a huge anticipated growth of connected devices from the 6.4 billion devices today, to an expected 20 billion connected devices by 2020[2].

The UK manufacturing sector contributes approximately £6.7 trillion to the global economy (circa 11% GVA) and employs around 2.6 million people. In 2017, there were 266,000 registered small to medium sized enterprise (SME) manufacturing businesses (5% by quantity of all SMEs) which accounted for 15% of the turnover of all SMEs[3].

Background

One major challenge identified is enabling the adoption of digital technologies for the SME community[2]. The same report suggested that the majority of SMEs worry about adopting Industrie 4.0 or 4th Industrial Revolution (4IR) practices due to the fear of high investment costs, lack of technology knowledge and a skills gap within their own business. Fuelling this fear is increasing pressure to reduce costs and improve services, and a “fire-fighting” or “break-fix” operational model.

Many SME businesses are today worrying about operational problems and delivering jobs on time and within specification. They generally do not have the flexibility or budget to grow digital skills, know what technology or skills they require or move their core operation outside their comfort zone.

Objectives

It is hoped that through educating and demonstrating low-cost digital technologies, SMEs may become more familiar with what is possible and how to approach on boarding such capabilities to enable them to become more operationally efficient, competitive and increase the value of their product offering.

It was recently highlighted that there were few places for SME businesses to go to see 4IR technology in action. Most available demonstrations of 4IR technologies had a high price point, the need for highly skilled “digital” staff and technology that was unfamiliar to them or not in context or at a scale to challenges they were facing. The importance of low-cost demonstrations was critical and a demonstrator which could be related easily to an SME business operation.

The Advanced Manufacturing Research Centre (AMRC), part of the University of Sheffield, has put together two demonstrators to highlight 4IR technologies on a low-cost manufacturing platform. Two levels of target system cost were identified, one below £500 and one below £5,000. The reason for these thresholds was to accommodate both ultra-low cost production equipment, and legacy equipment that had a retained high value, but without embedded digital technologies.

2. METHODOLOGY

2. METHODOLOGY

Digitalisation of UK manufacturing is aimed at increasing the productivity and expanding the service offer of the UK manufacturing sector. A main enabler of this is being achieved through increasing the availability of production data. This data can not only offer operational insight and support productivity improvements, but also itself have a value that may be offered as a service along with the physical asset being manufactured. Particularly within the aerospace sector, traceability and the provenance of component manufacture and assembly is essential to some degree. Having production data associated with the primary component manufacture could be significantly important for the future of the industry. The prime aircraft manufacturers are requesting increased volumes of data to support the historic traceability requirements of each manufactured aircraft.

Requirements

In speaking with many SME manufacturers, it is clear the sector has a thirst for data; this data could support them expanding upon their production offer. There are a number of basic production metrics that may be captured from legacy equipment and offer value to an SME using simple and low-cost sensing, including, but no limited to:

Overall Equipment Effectiveness (OEE):
A method of measuring productivity or utilisation by calculating the percentage of production time that is truly productive. 100% OEE means 100% quality (all parts are good), 100% performance (as fast as possible) and 100% availability (i.e. no stoppages).

Operating Cost:
The cost associated with operating the equipment over a specified time period or per manufactured component.

Machine Condition:
This provides an overview of the current machines health, e.g. if a spindle or bearing is producing higher than expected vibrations, it may require maintenance.

Process Control:
Measuring specific parameters related to the process may indicate whether a component may or may not be within the required manufactured tolerance. E.g., high vibrations may indicate a worn tool or incorrect machine speed/feed that may influence the quality of the manufactured component.

For a successful low cost demonstration of 4IR technologies specifically focused for SME and legacy systems, it was concluded that a selection of the above attributes could be gathered using a relatively simple sensor setup. The two levels of demonstration identified were:

- **Sub £500 ultra-low-cost demonstrator using hobby/prototyping hardware where a candidate system would be typically up to £20k.**
- **Sub £5,000 robust industrial demonstrator using industrial certified high fidelity hardware for a candidate system of +£20k.**

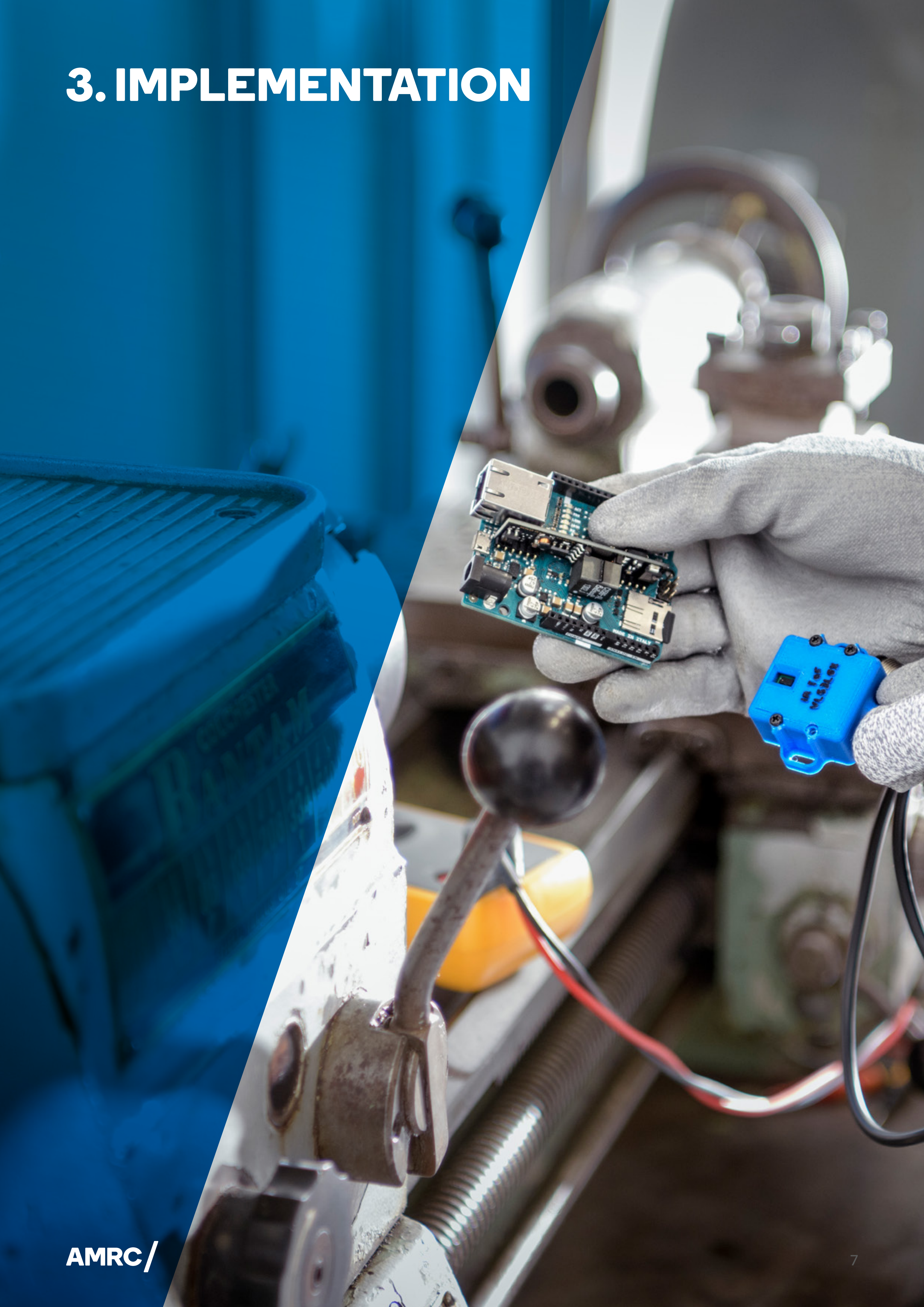
OEE can be attributed to a number of different metrics. Here, a simple indication of OEE for legacy hardware was gathered through monitoring the power consumption of the machine. If the current drawn by the machine was above a calibrated limit, the machine was identified as running. Using the on verses off time, a percentage operating time was calculated. This is, however, not true OEE, as the machine running doesn't fully indicate whether the machine is manufacturing a component or simply running in air. As a simple demonstration, this was deemed acceptable, and could also give an indication of spindle run hours that could be used to trigger a service. For true OEE calculations, additional data would be required including vibration or human input.

Operational cost was calculated simply from measured current, I, using a current transformer (CT) sensor where the apparent power, $P=IV$, using the assumption that the voltage V, was a constant 240 V RMS. Measuring real-time current allowed both the instantaneous cost and cumulative running cost to be calculated simply by additionally knowing the KWh unit cost of the supplier tariff. The instantaneous cost for a given time period $\Delta t = t_1 - t_0$ measured in seconds is shown below where the tariff rate is provided in pence/kWh.

$$\text{£ / hr} = \frac{\text{Tariff Rate} \times \Delta t}{360 \times V \int_{t_0}^{t_1} I(t)dt}$$

Machine condition and process control was deemed not possible for the Colchester Lathe due to low volumes of data (limited by hardware capability) but would be possible using higher fidelity data on the Bridgeport Turret Mill. Vibration/acceleration sensors would normally be used to monitor both machine health and process quality, however, in our system the sampling frequency achieved was too low to harness any useful insight (due to low-cost of the hardware used).

3. IMPLEMENTATION



3. IMPLEMENTATION

Two candidate machines were selected to demonstrate low-cost 4IR sensor technologies. Each one had a separate data collection system installed.

Colchester Bantam Lathe (Circa 1956)

The first machine, a 1956 Colchester Bantam lathe seen in Figure 1 was fitted with ultra-low cost hardware ~£400. Table 1 below lists the sensor hardware that was selected for the demonstration:

Sensor	Measuring	Sampled Rate	Cost
2x 1-axis accelerometers	Gearbox and carriage vibration	58 Hz	£10
3-axis accelerometer	Motor housing vibration	58 Hz	£25
Digital temperature	Motor housing temperature	58 Hz	£3
Current transducer (CT)	Electrical current	58 Hz	£60
Hall effect sensor	Spindle rotational speed	58 Hz	£25
Time of flight proximity sensor	Carriage position	58 Hz	£15

Table 1: *Sensor hardware selected for the Colchester Bantam lathe*

An accelerometer was fitted to each of the motor (Adafruit MMA8451,[4]), gearbox and carriage (Adafruit ADXL335,[5]) to measure vibrations across the machine. The vibration data was used to indicate a number of parameters including imbalance and poor part or tool setup. A digital temperature sensor (Maxim DS18S20,[6]) was installed in the motor drive unit. The headstock temperature was also considered an important component within the machine to monitor temperature, however without stripping the machine down was thought too invasive and not a simple retrofit for this project.

A simple split core current transformer (CT) sensor (LEM ATO-10-B333-D10; 1:1000, 10A,[7]) was fitted around the single-phase live input cable within the electrical cabinet of the machine. The carriage position was measured using a Time of Flight (TOF) distance sensor (Adafruit VL53L0X,[8]) mounted to the body of the machine and small reflector device fixed to the movable carriage. The spindle speed was determined using a hall-effect digital position sensor (Honeywell SR3 Series,[9]) and neodymium magnet fixed to the rotation spindle.

Figure 1: *A 1956 Colchester Bantam lathe retro-fitted with ultra-low cost sensing equipment attached.*

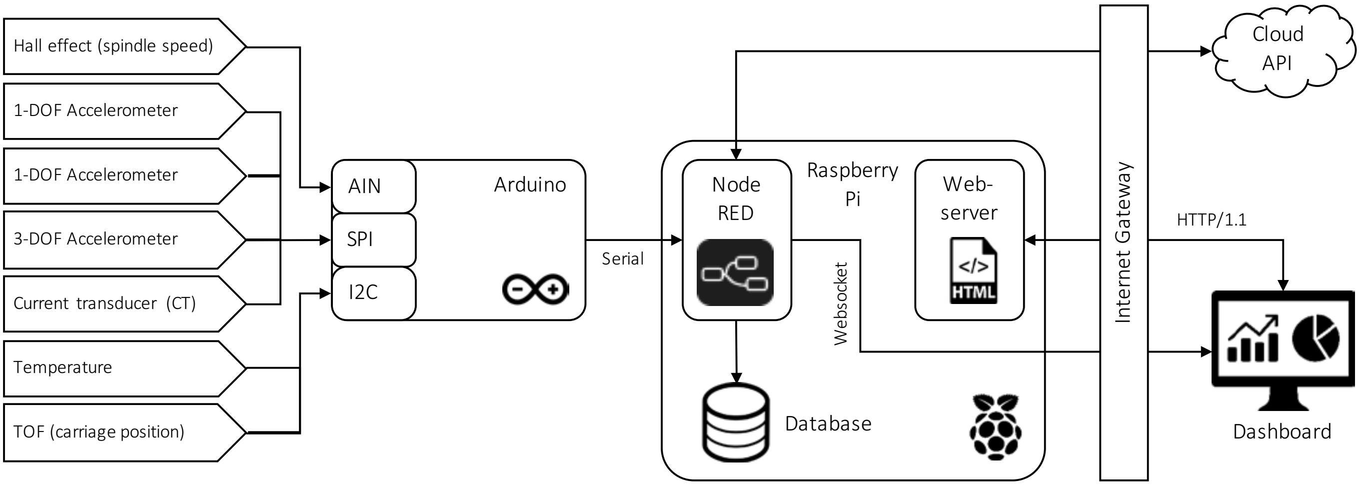


Figure 2: *Colchester Bantam lathe system Architecture.*

The measurements from the sensors fitted to the Colchester Bantam lathe were collected using an Arduino (Mega 2560, £35,[10]) microcontroller with real-time clock (RTC) capabilities. The data was acquired with pre-processing (e.g. averaging or biasing) before being sent via the Arduino serial port to a Raspberry Pi (model 3B, £34,[11]). The role of the Raspberry Pi was to act as a network gateway, wireless access point, edge data processor and webserver. Figure 2 shows the system architecture that was used to connect the Colchester Bantam lathe.

The raspberry Pi was installed with Raspbian v4.14[12], a Linux based Operating System (OS) and NodeRED[13]. NodeRED is a graphical wireframe programming tool for rapid prototyping of event driven data. A simple data flow as seen in Figure 3 was constructed to manage the event driven data. As data from the Arduino arrived on the serial port of the Raspberry Pi, NodeRED was used to manipulate that data, parse it into a number of different structures to make it available across several services. These services included an internal SQL database, cloud based SQL database and a HTML5 website using simple websockets. This could be extended to other services e.g. Simple Object Access Protocol (SOAP), Representational State Transfer (REST) Application Programming Interface (API) or Open Platform Communication (OPC) easily in NodeRED.

The individual data packets arrived in NodeRED at a frequency of approx. 58 Hz. All individual messages that arrived within a 1-second interval were bundled together into a single array. A moving average was also calculated at a 1-second interval, and was passed to the outgoing websocket node to reduce the processing and traffic required on the client web browser.

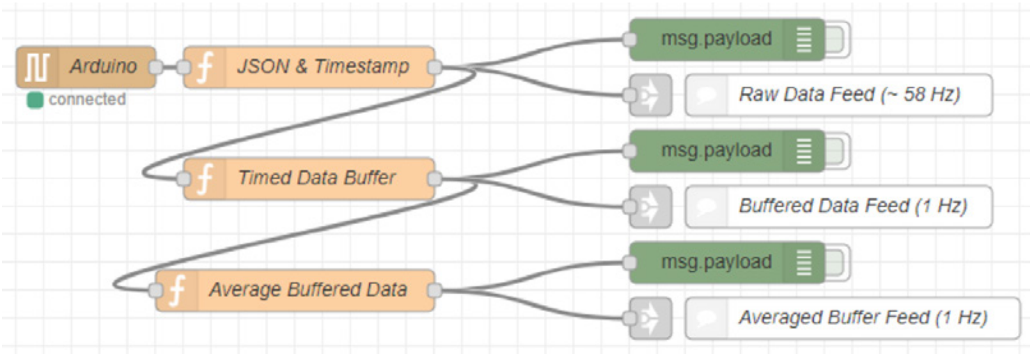


Figure 3: *NodeRED flow used for managing data messages on the Raspberry Pi.*

A dashboard, shown in Figure 5, hosted on the Raspberry Pi was used to visualise the sensor data and derived metrics using a standard HTML5 and JavaScript interface with an easy to use Bootstrap Framework applied for appearance. Data was sent on an event basis to the website using the websocket protocol at an average rate of one per second. Websockets differ from traditional website protocols such as HTTP and REST, in that a TCP socket is maintained between the client and server so that as the server publishes new data, the client can act asynchronously upon receipt this data by updating the visualisation on the client's browser without having to reload the webpage. Websockets were used in this instance as a way to expose the data as close to real-time as possible without having large network and redundant traffic that would be generated during tradition Asynchronous JavaScript and XML (AJAX) or long-polling methods. The websocket is simply setup in NodeRED using the outgoing websocket node as shown in Figure 4.

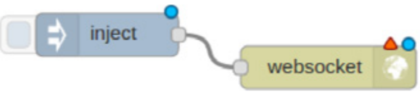


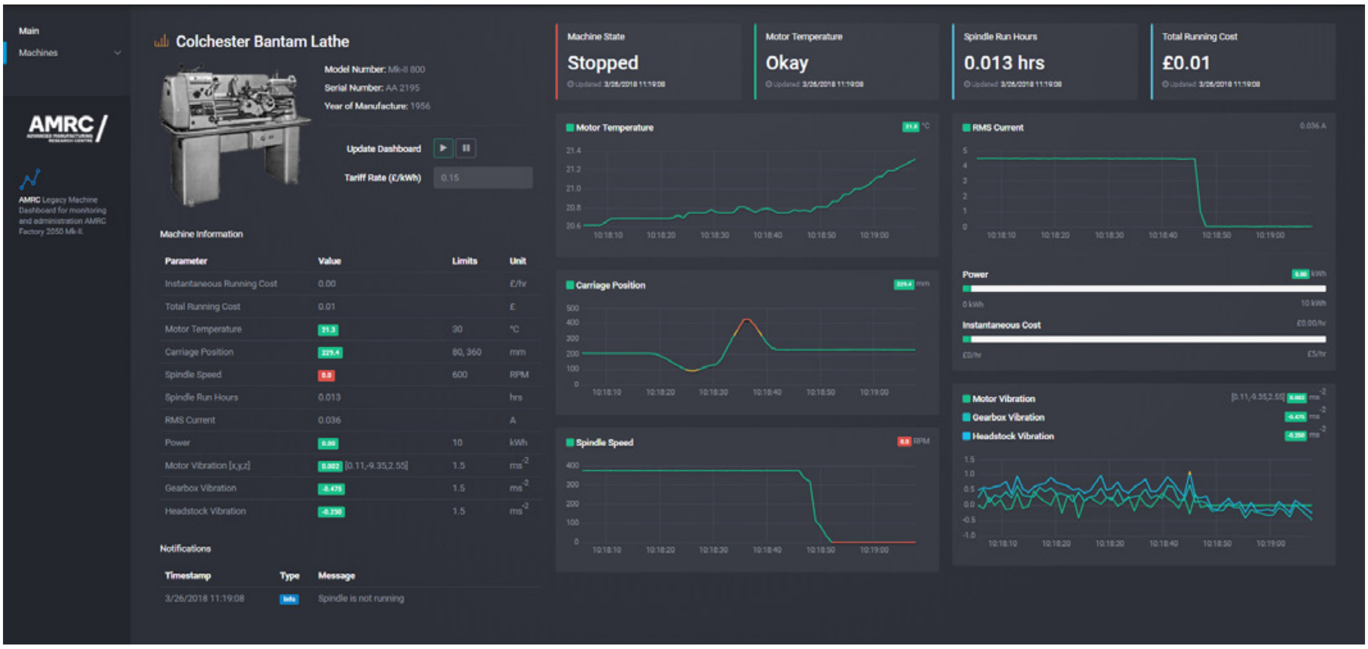
Figure 4: *Outgoing websocket node in NodeRED.*

On the client website this is again simple configured using JavaScript as defined below, to connect to the websocket server:

```
let url = "ws://host:port/endpoint";
let socket = new WebSocket(url);
```

Another advantage why standard HTML5 and JavaScript technology was chosen for the demonstration was that most devices today have the capability of rendering website content (e.g. laptops, smartphones, tablets etc.), hence the demonstration is device and platform agnostic.

Simple alerts were also setup within the web interface to demonstrate basic notification methods for flagging issues. Temperature, vibration and carriage position limits were defined. If the machine drifted outside these limits, a notification was raised. This was demonstrated through indicators in the website dashboard, but also could have the ability to flag issues via email or text message if required. In addition, the charts were colour-coded based on the current state of the parameter being plotted for intuitive status identification as shown in Figure 5.



Colchester Bantam Lathe

Model Number: Mk-II 800
Serial Number: AA 2195
Year of Manufacture: 1956

Tariff Rate (£/kWh): 0.15

Machine State: Stopped (Updated: 3/26/2018 11:19:08)
Motor Temperature: Okay (Updated: 3/26/2018 11:19:08)
Spindle Run Hours: 0.013 hrs (Updated: 3/26/2018 11:19:08)
Total Running Cost: £0.01 (Updated: 3/26/2018 11:19:08)

Machine Information

Parameter	Value	Limits	Unit
Instantaneous Running Cost	0.00		£/hr
Total Running Cost	0.01		£
Motor Temperature	21.3	30	°C
Carriage Position	229.4	80, 360	mm
Spindle Speed	0.0	600	RPM
Spindle Run Hours	0.013		hrs
RMS Current	0.036		A
Power	0.00	10	kWh
Motor Vibration [x,y,z]	0.002 [0.11,-9.35,2.55]	1.5	ms^{-2}
Gearbox Vibration	-0.475	1.5	ms^{-2}
Headstock Vibration	-0.250	1.5	ms^{-2}

Notifications

Timestamp	Type	Message
3/26/2018 11:19:08	Info	Spindle is not running

Figure 5: *Website dashboard developed to visualise data collected for the Colchester Bantam lathe.*

Bridgeport Turret Mill (Circa 1980)

On the second machine, a 1980's Bridgeport Turret Mill seen in Figure 6, higher fidelity (and increased cost) sensing and processing hardware was deployed to investigate additional metrics and return an additional investment. Table 2 opposite lists the improved sensing hardware selected for the machine.

Three single axis accelerometers (TE TE805-0050-000,[14]) were attached to the outer casing of each the motor, top of the gearbox and close to the spindle. Spindle speed was measured using a retro-reflective photoelectric sensor (Omron E3FA-RP21,[15]) and strip of reflective tape attached to the spindle to alter the

Sensor	Measuring	Sampled Rate	Cost
3x 1-axis accelerometers	Motor, gearbox and spindle vibration	5 kHz	£210
Laser proximity sensor	Spindle Rotational speed	100 Hz	£110
K type thermocouple	Motor housing temperature	10 Hz	£20
3x Current transducers (CT)	Electrical current (1 per 3 phase)	5 kHz	£160

Table 2: *Sensor hardware selected for the Bridgeport Turret mill.*

Figure 6: *A 1980's Bridgeport Turret mill with high fidelity sensor equipment attached.*

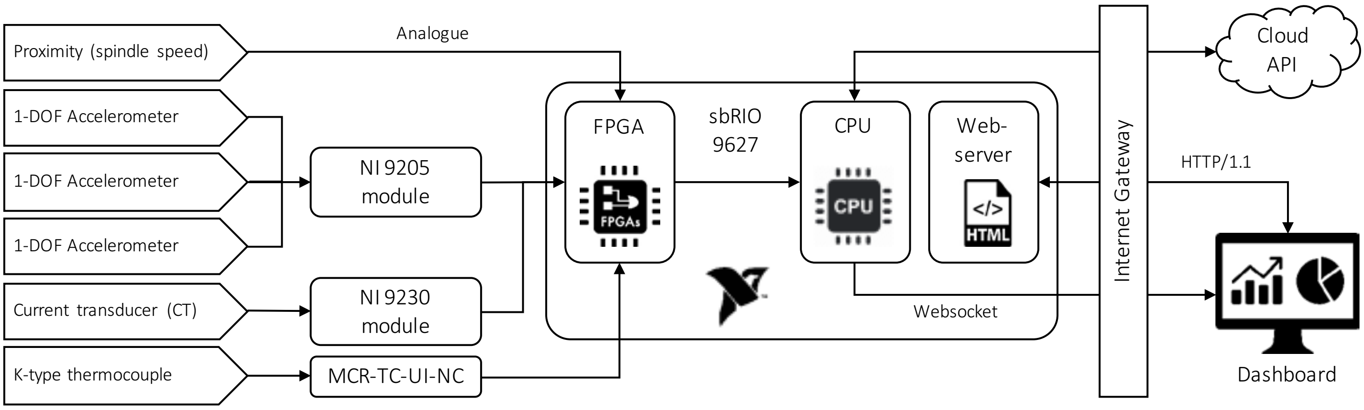


Figure 7: *Bridgeport Turret mill system Architecture.*

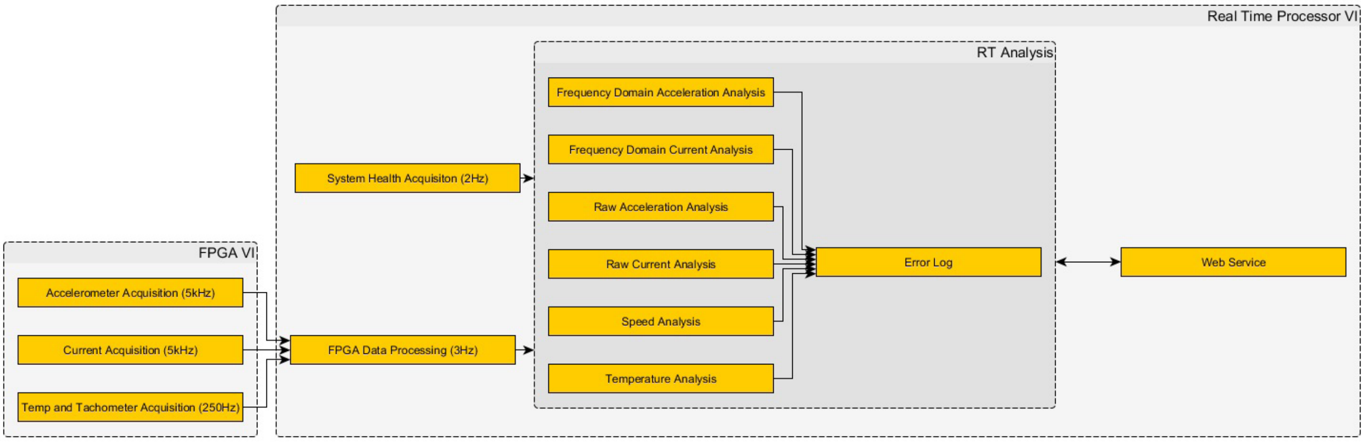
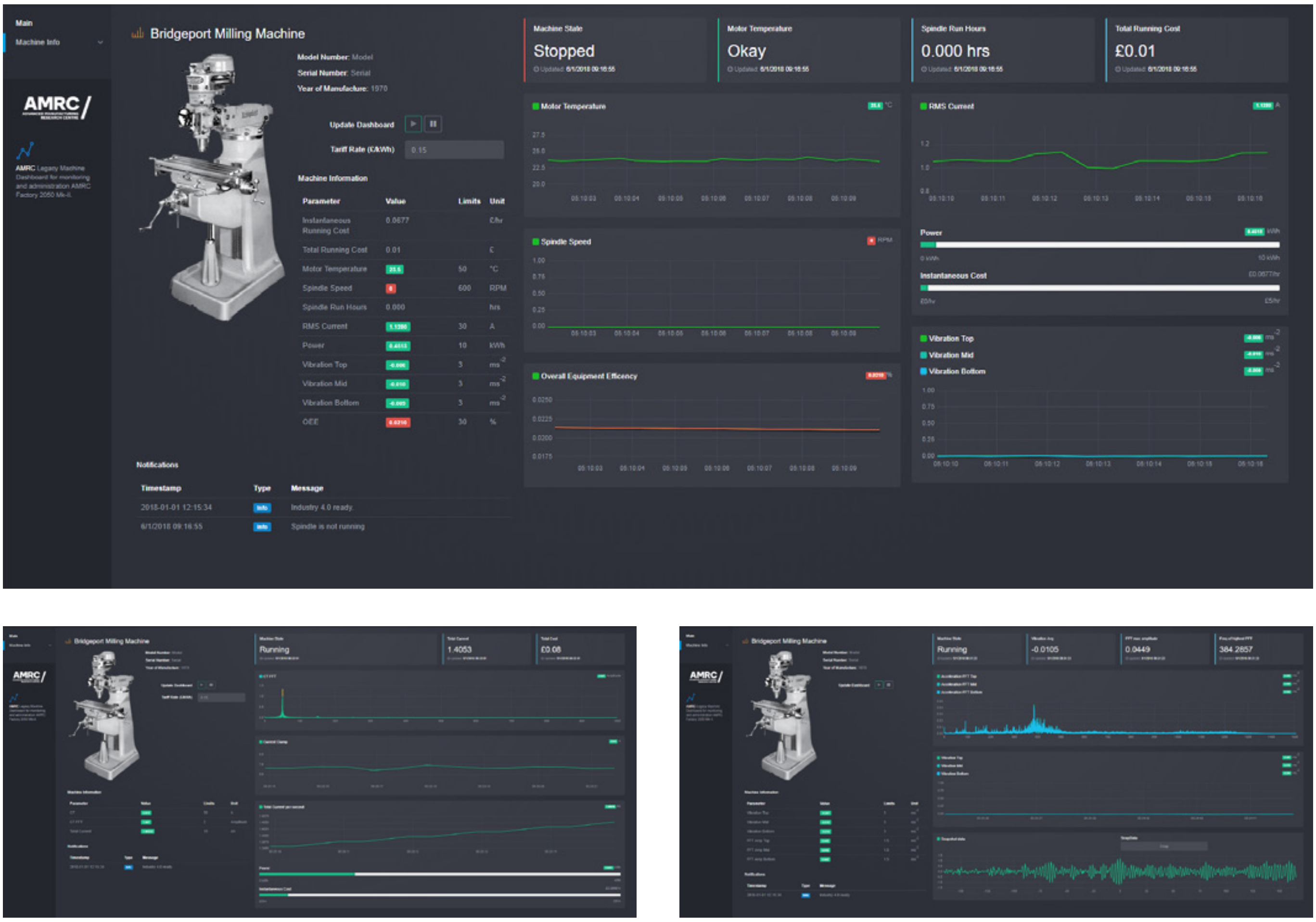


Figure 8: *Bridgeport Turret mill LabVIEW system Architecture.*

reflectance as it rotates. Temperature was measured using a K-type thermocouple (RS 872-2525,[16]) with range -60°C to +350°C. Current was measured using three split core current transformers (CT) sensor (LEM ATO-10-B333-D10; 1:1000, 10A,[7]), one for each phase. Figure 7 shows the basic systems architecture deployed on the Bridgeport Turret mill. Figure 8 provides a representation of the LabVIEW architecture used to manage the data collection and processing element of the system.

National Instruments equipment was chosen to collect and process the high frequency sampled data. NI equipment provides a robust and industrial solution for data capture. A NI Single Board Rio (sbRIO 9627, £1,500,[17]) was used as the main processing unit. Additionally, a range of input/output (IO) modules were required including a 3-Channel, 12.8 kS/s/channel, ±30 V, C Series Sound and Vibration Input Module (9230, £450,[18]) and a ±10 V, 250 kS/s, 16-Bit, 32-Channel C Series Voltage Input Module (9205, £770,[19]). In additional to the NI hardware, a Phoenix Contacts Thermocouple measuring transducer (MINI MCR-TC-UI-NC, £135,[20]) was also required for signal conditioning.

LabVIEW[21], a programming environment for use with NI equipment was used to construct the data acquisition software that was deployed on the sbRIO device. As with NodeRED, LabVIEW is a graphical programming tool using blocks with specific attributes to build up a programming flow to manage and process the incoming sensor data. The LabVIEW program was deployed on the sbRIO Field Programmable Gate Array (FPGA), for its high speed (possible down to nanosecond resolution) and on edge data analytics capability.



Machine Information

Parameter	Value	Limits	Unit
Instantaneous Running Cost	0.0677		£/hr
Total Running Cost	0.01		£
Motor Temperature	25.5	50	°C
Spindle Speed	0	600	RPM
Spindle Run Hours	0.000		hrs
RMS Current	1.1280	30	A
Power	0.4013	10	kWh
Vibration Top	-0.006	3	ms^{-2}
Vibration Mid	-0.010	3	ms^{-2}
Vibration Bottom	-0.005	3	ms^{-2}
OEE	0.0210	30	%

Notifications

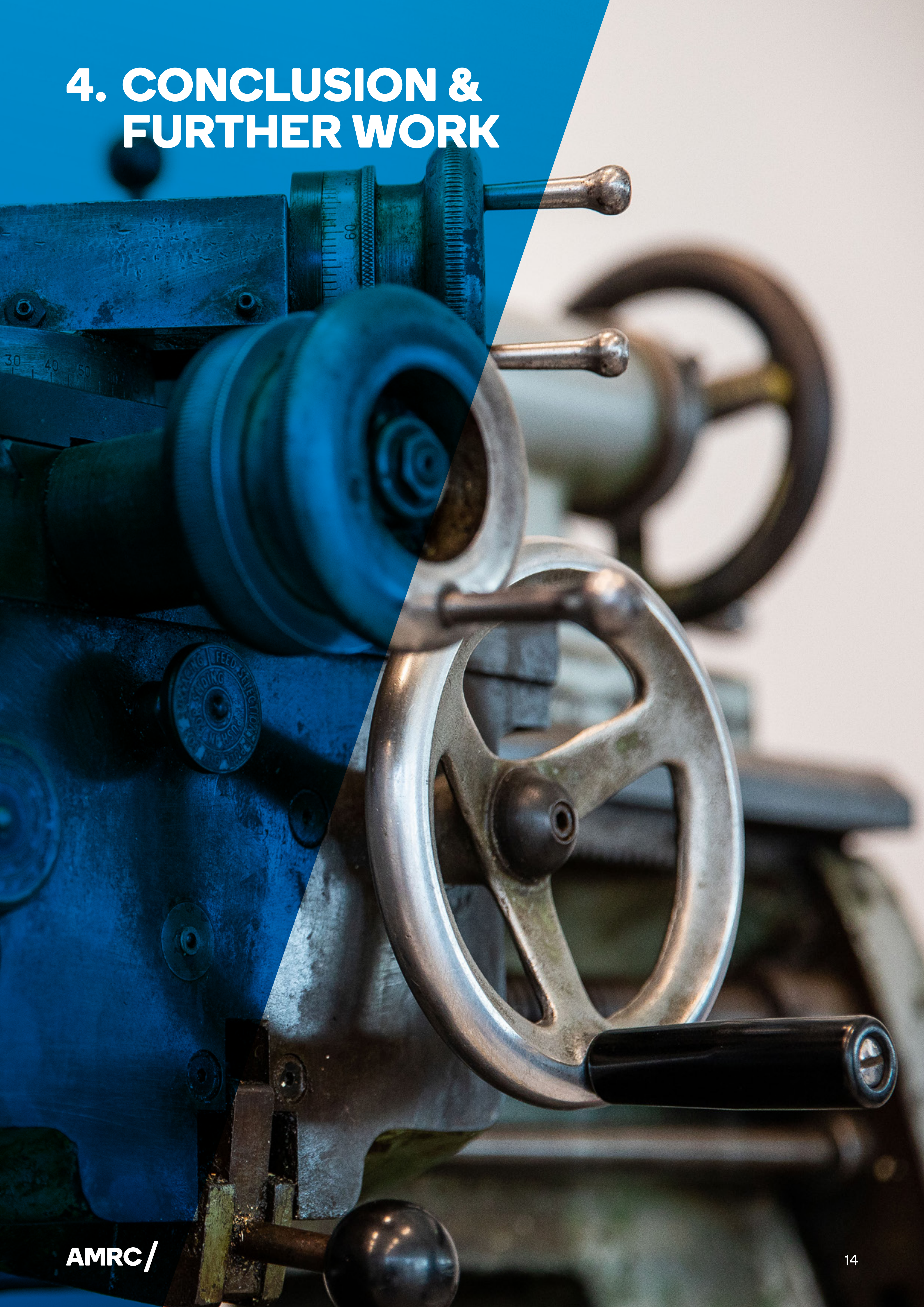
Timestamp	Type	Message
2018-01-01 12:15:34	info	Industry 4.0 ready
6/1/2018 09:16:55	info	Spindle is not running

Figure 9: *Website dashboards developed to visualise data collected for the Bridgeport Turret mill. Top: General overview; Bottom left: High frequency, detailed current analysis; Bottom right: High frequency, detailed vibration analysis.*

Again, as in the first demonstration, because of its simplicity and flexibility, the websocket protocol and a HTML5 website was used for consistency across both machines to visual the derived machine metrics. This also demonstrates the flexibility and capability of modern web applications. In this more advanced demonstration, Fast Fourier Transform (FFT) analysis was undertaken within the sbRIO hardware in real-time to perform frequency analysis of the vibration signals captured. FFT is a technique that can be used to identify artifacts within the frequency spectrum that may indicate changes in machine dynamics and for our machine, potentially its health.

The high speed data collected on the Bridgeport was collected at almost 100x the speed of the data on the Colchester. This meant that incredibly minute transient events could be recorded. The addition of the FFT on the vibration data meant that a visual evaluation could be made of the rotating components on the system to indicate their health, such as amplitude spikes of certain frequencies or a widening of the sidebands of a particular frequency. The FFT of the current signal gives insight into the health of the motor and other electrical elements. There are many other analysis options for generating insight from this high fidelity data such as bode plots, centre line plots and waterfall plots. A major finding of this project was that the insight made available from the extra data provided by the Bridgeport machine can only be maximised with the input of a Vibration Specialist, Condition Monitoring Engineer or similar. As such this becomes less viable as further work for the SME network, although is relevant to primes and larger manufacturers within the supply chain.

4. CONCLUSION & FURTHER WORK



4. CONCLUSION

It has been clearly shown that the AMRC demonstration of 4IR technologies has significant impact to support the adoption of digitalisation within the SME manufacturing community.

What has also become evident is that basic insight into production efficiency is likely to be of greater value than striving for high fidelity real-time dynamic analytics of vibrational signals. Simple productivity insight of efficiency and operational costs will deliver increased benefits for SMEs than detailed and complex condition based machine monitoring. The upfront cost associated with this basic insight is also significantly less than that required for condition based monitoring and predictive maintenance.

There is also a need for industrial hardware suppliers to offer lower cost but robust instrumentation options suitable for a SME business where the target asset for retrofit of sensing equipment is sub £20k.

FURTHER WORK

The next phase of this project would aim to optimise the data visualisation specifically for different roles within a business. Three main views have been identified which have varying degrees of required insight. These should be more associated around key performance indicators (KPIs) relevant for each role:

Operator role:
Would require information about the real-time status of the machine including temperatures, vibrations, speeds etc.

Business owner or line manager:
Would be interested in understanding OEE and productivity information.

Maintenance engineer:
Would require information around warnings and alerts that have triggered based on out of limits operations, which may include vibrational analysis information.

It has also been identified that another major barrier to adoption is around lack of skills within an SME business for software and sensor integration. A plug and play approach should be adopted for future iterations of hardware, similar to the approach adopted when buying a new smartphone. Simple information provided by the end user allows the device to be setup quickly and configured specifically for the end user's needs. It is anticipated there is no single one-size fits all machine monitoring package, so simple configuration and installation for a business owner is essential.

As part of future work, a wider view of the SME manufacturing landscape would be used to identify suggested configurations based on specific machine types. This might include different configurations for machine tools, looms, press tools or injection moulding equipment for a wider community.

There is significant benefit in evaluating commercially available hardware, and working with solution providers to support the needs of the SME community. In addition, it is essential to demonstrate a range of low-cost industrial hardware that is hoped will address the gap between being cost effective but also industrially supported and robust for a wide range of customisable solutions.

ACKNOWLEDGEMENTS

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AMRC Factory 2050
Europa Avenue, Sheffield, S9 1ZA
T: +44 (0)114 215 8200
E: f2050enquiries@amrc.co.uk
amrc.co.uk