Final Report

WP3.3.1 Closed Loop Liquid Resin Infusion

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ABOUT 5G-ENCODE

The 5G-ENCODE Project is a £9Million collaborative project aiming to develop clear business cases and value propositions for 5G applications in the manufacturing industry. The project is partially funded by the Department for Digital, Culture, Media, and Sport (DCMS), of the UK government as part of their 5G Testbeds and Trials programme. The project is one of the UK Government's biggest investments in 5G to modernise manufacturing.

The key objective of the 5G-ENCODE project is to demonstrate the value of 5G as part of industrial use case delivery within the composites manufacturing industry. It also is designed to validate the premise that using private 5G networks in conjunction with new business models can deliver better efficiency, productivity, and a range of new services and opportunities that would help the UK lead the development of advanced manufacturing applications.

The project will play a key role in ensuring that UK industry makes the most of the 5G technology and ultimately remains a global leader in the development of robust engineering capabilities when implementing complex composites structures manufacturing processes.

The project will highlight how 5G features such as neutral hosting and network slicing can be applied to transform a private 5G network into a dynamically reconfigurable network able to support a wide range of applications (URLLC/eMBB/MMTC) including industrial applications of Augmented Reality/Virtual Reality (AR/VR), asset tracking of time sensitive materials and automated industrial control though IoT monitoring and big data analytics. Such a dynamic network would enable new business models and creation of bespoke virtual networks tailored to specific applications or use cases.

A state-of-the-art test bed was deployed across three sites centred around the National Composites Centre in the Southwest of England. In support of the West of England Combined Authority (WECA) industrial strategy, the NCC plans to keep the test bed as an open access facility for the experimentation and development of new products and services for the composites industry after the completion of the 5G-Encode project. The location and nature of NCC's business would ensure the creation of an industrial 5G ecosystem involving multiple industry sectors and small and medium enterprises (SMEs).

The project consortium, led by Zeetta Networks, brings together leading industrial players (e.g., Siemens, Toshiba, Solvay), a Tier 1 operator (Telefonica), disruptive technology SMEs covering all aspects of network design, deployment, and applications (Zeetta Networks, MatiVision, Plataine), application performance as measured by probes (Accedian), world-leading 5G network research group (High Performance Networks Group in the University of Bristol) and the NCC representing the high value manufacturing industry.

EXECUTIVE SUMMARY

This report outlines the development of the 5G Closed Loop Liquid Resin Infusion (LRI) use case. LRI is a process used by the aerospace, automotive, marine and several other industries to create composite components. It has many benefits over prepreg, such as cheaper material costs and faster manufacturing times – however is highly dependent on the skill of the operator, is very manual, and often produces many scrap components when developing new parts. There is a need to automate LRI to make parts right-every-time, reduce the environmental impact by generating less scrap, and lower cost and manufacturing time.

The Closed Loop LRI system utilised 5G and digital technologies to improve the process. The system used a sensor array to monitor key LRI process variables and sent this data to a control model. The model decided how the process should be altered in real time and sent commands to a feedback system that implemented the decisions. A visualisation system used dashboards to display process data in real-time and generated a traceability report for each part. All sensor data and control commands were sent over 5G.

To enable a modern closed loop system to work effectively there are numerous requirements to consider. A high speed, low latency, highly reliable network is needed to transfer process data across. Next, because the amount of data needed to properly model a manufacturing process could be vast, the network needs to be able to handle large numbers of sensors connecting to it. In practice the sensors need to connect to the system wirelessly as attempting to connect a huge number of wired sensors is impractical. Finally, a high-performance computing capability – located on the edge – is needed to run complex models (for instance AI) that will control the manufacturing process. 5G has the potential to meet these requirements through characteristics including **Ultra-reliable low latency communication, edge computing**, and **massive Machine Type Communication** (allowing thousands of devices to connect to the network at once).

The system was initially tested on a 4G network to establish a baseline, and then tested on a bespoke 5G network to assess if there was a discernible increase in real world performance of the use case. Additionally, the system was tested on a low cost off-the-shelf/open source 5G network; its performance was assessed to understand if this cheaper system could allow smaller companies to leverage the benefits of 5G.

The Closed Loop LRI system realised numerous benefits. It led to reduced manufacturing labour costs of around 25% while the live dashboards gave engineers a clear view of the process and allowed them to reduce cure cycle time by around 50%. Using wireless 5G communication enabled the system to be flexibly deployed anywhere in the factory. Finally, the automatic generation of the part traceability report saved over 8 hour of engineering time and associated costs.

Overall, the use case was able to operate well over 5G, however network dropouts due to poor reliability caused some data loss – more work is required to enhance device stability on the 5G Standalone Open RAN network (5G SA ORAN).

Reliability issues were also seen with the off-the-shelf/open source 5G network.

There was not a discernible performance increase seen over the 4G baseline. The use case however was a small-scale demonstrator – it is likely that if the system was expanded to a more representative scale (such as an aircraft wing manufacturing process) the advantages of 5G would become visible.

CONTENTS

FIGURES

ABBREVIATIONS

3GPP	3rd Generation Partnership Project
AI	Artificial Intelligence
COTS	Commercial off the shelf
DoC	Degree of Cure
eNB	evolved Node B
gNB	next Generation Node B
GPS	Global Positioning System
HSS	Home Subscriber Service
IoT	Internet of Things
IP	Internet Protocol
JSON	JavaScript Object Notation
LRI	Liquid Resin Infusion
LTE	Long Term Evolution (AKA 4G)
MEC	Multi-access Edge Computing
MME	Mobile Management Entity
mMTC	Massive Machine Type Communication
MQTT	Messaging Queue Telemetry Transport
NCC	National Composites Centre
NSA	Non-Standalone (in relation to 5G)
NUC	Next unit of Computing (a bare bones miniature PC)
OAI	Open Air Interface
O-RAN	Open-RAN
ORS	Online Resin Monitoring Software (Synthesites Ltd)
OSA	OpenAirInterface Software Alliance
PDN	Public Data Network

PDU	Protocol Data Unit
PLC	Programmable Logical Controller
PLMN	Public Land Mobile Network
PPS	Pulse Per Second
RAN	Radio Access Network
RF	Radio Frequency
SA	Standalone (in relation to 5G)
SDR	Software Defined Radio
SE	Systems Engineering
SME	Small to medium enterprise
SPGW	Serving & PDN Gateway
SQL	Structured Query Language (relational database)
Tg	Glass transition temperature
UE	User Equipment
URLLC	Ultra-Reliable Low Latency Communication
USB	Universal Serial Bus
USRP	Universal Software Radio Peripheral

INTRODUCTION

Industrial Challenge

Liquid resin infusion (LRI) is a process used by the aerospace, automotive, marine and many other industries to create composite components. These can range from boat hulls to full aircraft wings, such as on the Airbus A220. It offers higher rate and lower cost production compared to other methods used to make composites (such as prepreg moulding, which has higher material costs, and longer processing times). The technique however is highly dependent on the skill of the operator, is very manual, and often produces many scrap components when developing new parts.

As industry grows its use of LRI, there is a need to improve the process to enable parts to be made 'right first time' and 'right every time' - lowering the cost and time of developing new components and reducing the environmental impact of composite production by generating less scrap.

These improvements to LRI composite manufacturing can be achieved through data analysis and automation of the LRI process by the application of digital and 5G technologies.

Project Objectives

The first stage towards enabling 'right first time'/'right every time' manufacturing is automation. Prior to this project the LRI process was almost entirely manual. **The purpose of this use case was to develop a system that could automate elements of LRI process** by using closed loop manufacturing.

Achieving this objective would enable:

1. Reduction in labour costs
2. Reduction in manufacturing time (and thereby cost)
3. Improvement in part quality

Purpose of 5G

Why 5G?

Due to the time sensitive nature of the LRI process, closed loop manufacturing systems require process data to be captured, sent, and processed in real time. This data can then be acted upon to alter process parameters, such as temperatures and pressures, thus steering the process to a successful outcome.

To enable a modern closed loop manufacturing system to work effectively there are numerous requirements to consider:

- A **high speed, low latency, highly reliable network** is needed to transfer process data across.
- Because the amount of data and sensors needed to properly model a manufacturing process could be vast, the **network also needs to be able to handle large numbers of sensors** connecting to it. Capturing data in this way is also critical in developing digital twins.
- In practice the sensors need to **connect to the system wirelessly** as attempting to connect a huge number of wired sensors into a network is impractical.
- A high-performance **computing capability – located on the edge** – is needed to run complex models (for instance AI) that will control the manufacturing process.

5G has the potential to meet these requirements through characteristics such as mMTC, URLLC, and edge computing.

The Closed Loop LRI system used an **IoT sensor array** to capture data on the manufacturing process, and this data was sent to a **control model** over a 5G network. Control decisions from the model were also sent over 5G to the **real-world feedback system.**

This use case was performed on a small scale to prove the concept of using 5G in closed loop manufacturing in an industrial setting, meaning the capabilities of 5G were not fully utilised in practice – however as this system is developed further (for example on a 17-meter aircraft wing manufacture) these 5G benefits would likely be required.

Assessment Methodology

To assess 5G properly, the Closed Loop LRI system was first tested on a **local 4G network**. After, this the system was tested in the same way on a **local 5G network**. The performance of system was assessed and compared on 4G and 5G respectively to establish what – if any – real world performance increase could be seen when switching to 5G.

The 5G network used by this use case was a bespoke system design and developed for the 5G ENCODE programme and was deployed at the NCC HQ in Bristol, UK. The network was a **5G SA system**. Full details of the network can be read in report 5G Encode Platform Commissioning Report[1].

In addition to the 4G baseline and bespoke 5G SA network, the use case was also tested on a **5G NSA network developed by Toshiba**. Purchase and installation of full scale 5G networks in an industrial environment is expensive, costing hundreds of thousands of pounds at a minimum. These costs are prohibitive for SMEs to adopt 5G and realise its benefits. To address this Toshiba developed a 5G network using COTS hardware and open-source software. This network was an order of magnitude cheaper to purchase and install than a standard full scale 5G network.

The viability of using a COTS/open-source low cost 5G network in an industrial environment was assessed by testing the performance of the Closed Loop LRI system on Toshiba's 5G NSA network.

The performance of the use case on the 4G and 5G SA networks can be found in the section 5G Industrial Assessment, while performance on the Toshiba network is found in the section Toshiba 5G NSA.

[1] https://www.5g-encode.com/media-and-publications (see 5G Encode Platform Commissioning Report)

OVERVIEW

The Liquid Resin Infusion Process

Process Overview

A composite is a form of material that takes two different material types and combines them together to create a single material structure with performance greater than that of the individual constituent materials. A common example of a composite is a carbon fibre reinforced plastic – the carbon fibres form the base strength of the material structure while the plastic holds the fibres together. Composites typically have higher strength-to-weight ratios than metallics, making them attractive to aerospace and many other industries.

The LRI process is one of the two primary techniques used to create composites parts (the other being prepreg moulding). It involves placing dry fibres in a mould tool cavity and then infusing liquid resin (plastic) into the fibres under vacuum pressure. The stages of the LRI process are shown in Figure 1.

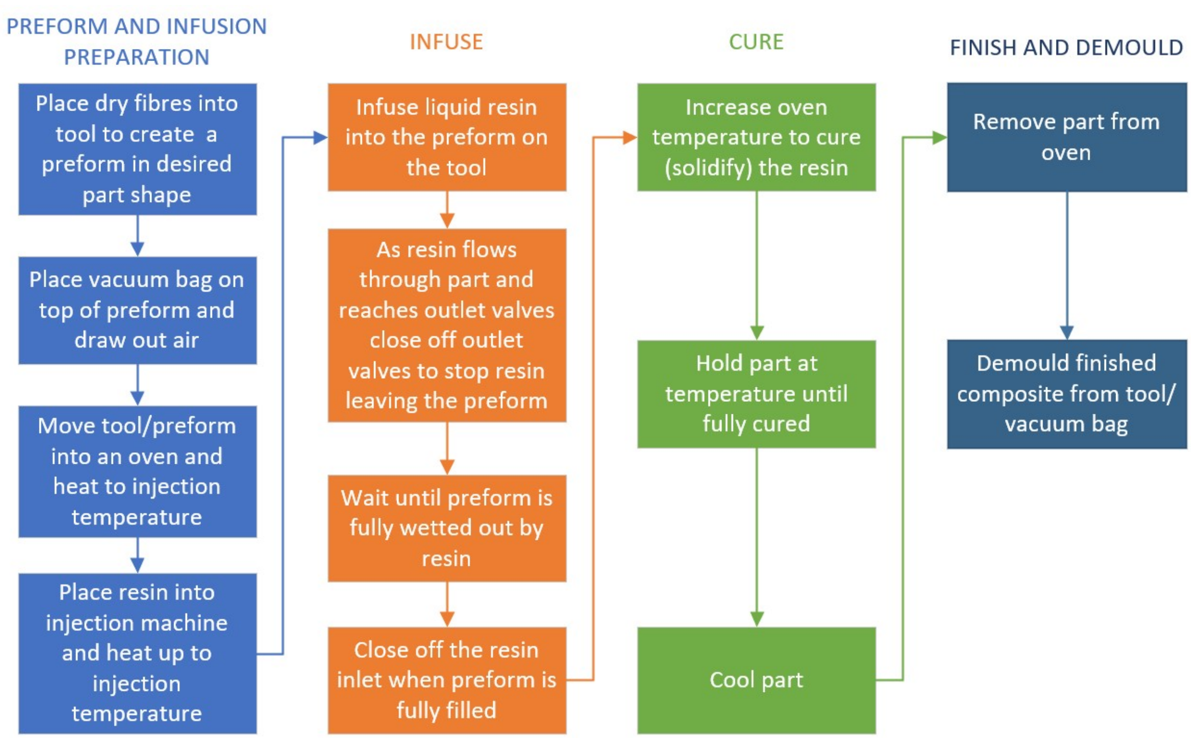

Figure 1 - The stages of the LRI process

LRI Manufacturing Equipment

The manufacturing system used to make composites by LRI typically has 3 main elements:

1. **Tool and vacuum bag**
   a. *The tool is where dry fibres are placed to form the part shape (known as a preform).*
   b. *The vacuum bag is placed onto the preform to form a mould cavity.*
2. **Oven**
   a. *This used to heat the tool/preform to the required injection temperature.*
   b. *After the infusion phase the oven temperature is increased to cure (solidify) the resin.*
3. **Resin injection machine**
   a. *This is used to hold the liquid resin and heat it to the required injection temperature.*
   b. *The resin needs to be heated to reduce its viscosity and make it easier to infuse into the dry fibre preform.*
   c. *The machine infuses the liquid resin into the fibre preform via a pipe.*

Images of the three elements can be seen in Figure 2, Figure 3, and Figure 4. For this use case a silicone vacuum bag was used.

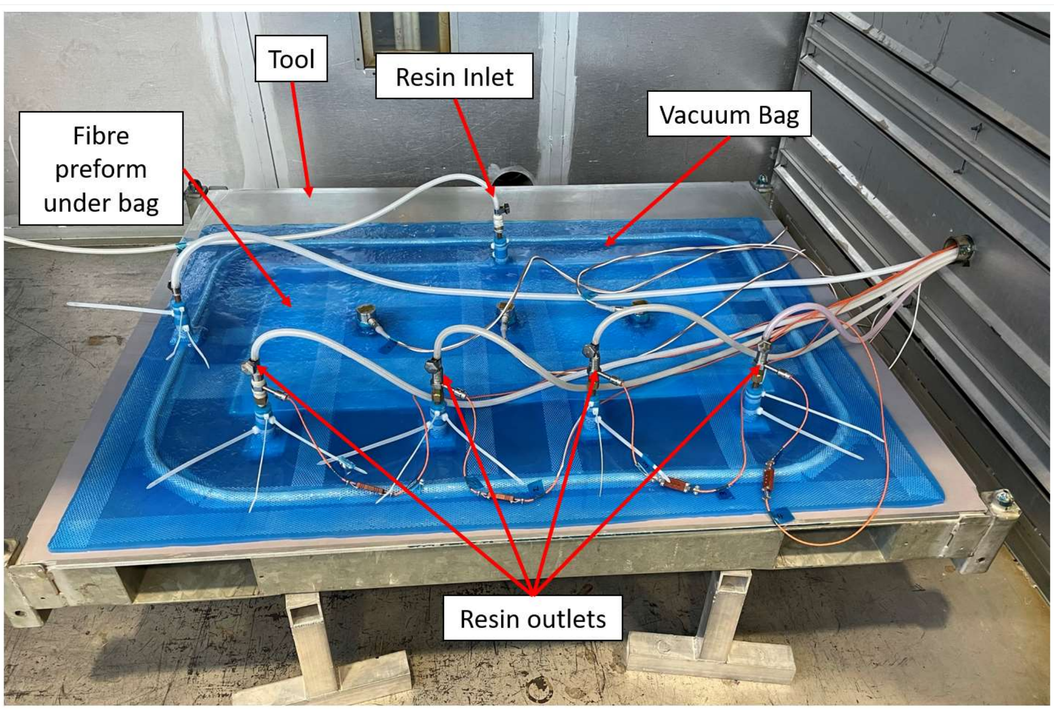

Figure 2 - Flat panel aluminium tool with a silicone vacuum bag

Figure 3 - Industrial oven

Figure 4 - Resin injection machine

Top Level Use Case Architecture

The Closed Loop LRI system comprised of two parallel systems. First was the system that would automatically control elements of the LRI process, named the Closed Loop Control System. Second was the system that would visualise the process data to engineers, this was called the Data Visualisation System. High-level architectures of both systems are shown in Figure 5 and Figure 6.

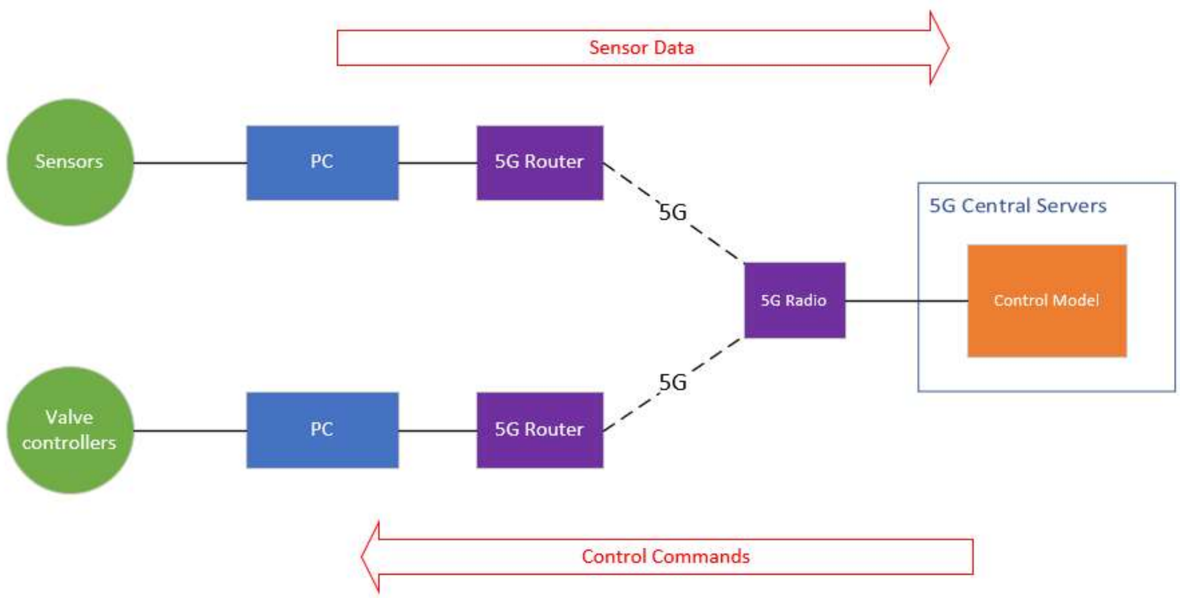

Figure 5 - Top level Closed Loop Control System architecture

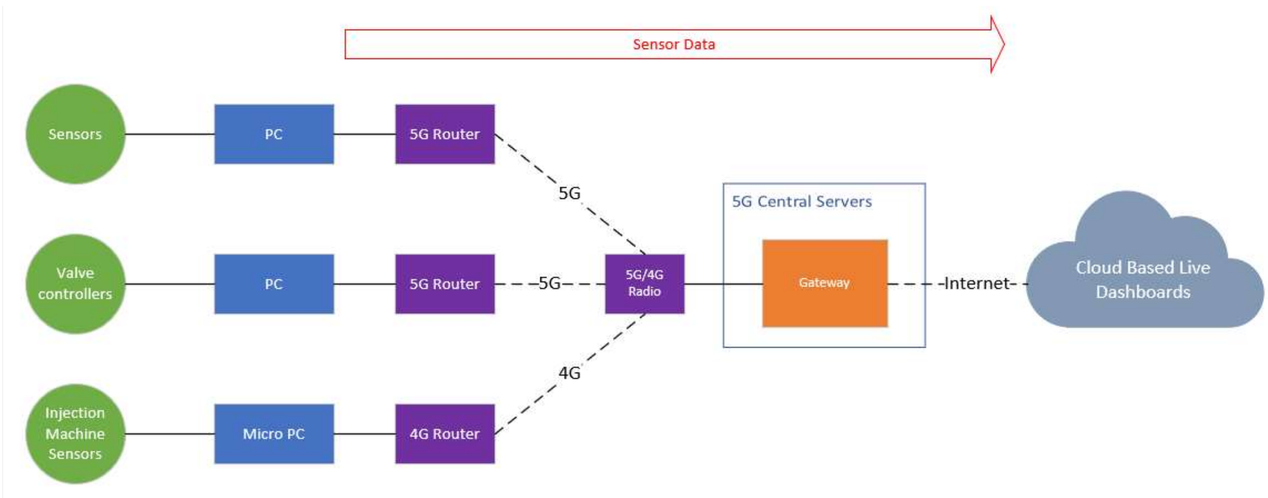

Figure 6 - Top level Data Visualisation System architecture

Closed Loop Control System – The system used a **sensor array to capture LRI process data**. The resin flow location was the key piece of information needed for control. This data was sent wirelessly over the 5G network to a control model (hosted on the 5G edge compute servers). The **control model used the data to make decisions** on what should happen in the process, and then sent these commands (over the 5G wireless network) to the feedback system to be implemented in the real world. The **feedback system had numerous valve actuators that could control resin outlet lines** and actuated these based on the control models commands.

Data Visualisation System – The system collected process data from three sources: the **sensor array** (resin characteristics, temperatures), **feedback system** (valve open/close status), and the **injection machine** (machine parameters). To enable the injection machine to stream data an IoT micro-PC and a router were integrated into it. All data was sent over the wireless 5G network[2] to a cloud gateway, which then forwarded the data onto a Microsoft Azure cloud platform. The data was stored in a data warehouse, and this was then **visualised on three separate dashboards**. The two live dashboards displayed the **process variables in real-time** (resin monitoring, and injection machine). The third dashboard displayed a **part traceability report** which gave a full data history of the manufacture.

Detailed architectures and descriptions of each system can be found in Use Case Development and Investigation.

[2] The injection machine used 4G to send data as suitable DIN-rail mountable industrialised 5G routers were not available at the time of the project.

Measures of Success

This section details the factors that will be measured to determine the success of the system.

Use Case Metrics

The following metrics have been used to measure the success of the use case:

Reduction in manufacturing labour time

How is it measured: Labour time saved or avoided

Unit: % reduction

Detail: Automating elements of the LRI process reduces the need for labour. Highly skilled operators are often doing low-value tasks in LRI, the Closed Loop LRI system will automate these low value activities, reducing the time (and cost) for part manufacture. This also frees up operators to perform higher value activities elsewhere in the factory.

Reduction in time to generate part traceability report

How is it measured: Engineer time

Unit: % reduction

Detail: Collating together manufacturing data from various sources (such as data loggers and machines) into a spreadsheet, time-syncing them, and creating graphs is a time-consuming exercise. Nevertheless, this is a critical activity for understanding what happened during manufacture for traceability and part insight. This system sought to perform the task automatically by collection and visualisation of data on dashboards.

Enhanced process insight

How is it measured: Variables monitored during manufacture are displayed on a single platform

Unit: Number of variables

Detail: Presently, little process monitoring is performed either mid or post-manufacture in LRI. If it is performed engineers must often look at multiple platforms/systems to view the data. Increasing the number of variables monitored during the process and displaying these on a single, easy to understand platform allows engineers to make data driven decisions to improve the process and part quality.

System Flexibility

How is it measured: Level of difficulty in redeploying system to other LRI processes

Unit: N/A

Detail: The combination of an IoT data capture architecture and use of wireless 5G allows the system to be deployed to any LRI process, anywhere in the factory. This means the benefits enabled by the Closed Loop LRI system are not locked to a single process/area.

Network Metrics

The following metrics have been used to measure the success of 5G on the use case:

Latency

How is it measured: Time taken for data to go from the Sensor Array to the Control Model (or from the Control Model to the Feedback System)

Unit: milliseconds

Detail: Low latency is critical for control-based systems; if latency is high, the commands may be slow to execute and cause quality or safety issues.

Reliability

How is it measured: Percentage of the time the 5G network was ‘up’ during a manufacturing cycle (network up time ÷ total manufacturing time)

Unit: %

Detail: Reliability is even more critical than latency, as if a network drop out occurred, data or commands may fail to send/be received and again cause quality or safety issues.

Packet loss

How is it measured: % of data lost in transit over the network

Unit: %

Detail: If data or commands are lost over the network they will not be properly received or executed.

Wireless performance

How is it measured: Wireless signal strength and consistency in industrial setting

Unit: N/A

Detail: Factories are typically challenging environments for wireless networks; large metallic building framework, heavy machinery, and electrical interference can cause signal issues. The 5G network must be able to provide strong consistent signal despite these factors.

Closed Loop LRI System Requirements

The requirements for any closed loop manufacturing system are threefold: monitor the key variables, use this data to decide how the process should be altered, and then implement the decisions. To meet these core requirements, the Closed Loop LRI system developed three sub-systems: Sensor Array, Control Model, and Feedback System. These are shown visually in Figure 7.

A data visualisation platform is not strictly necessary for a closed loop control system to work, however the ability to view process data in real time (or assess the data after the process) provides significant benefits, as outlined above in Use Case Metrics. Because of this, a fourth sub-system – the Data Visualisation System – was also developed.

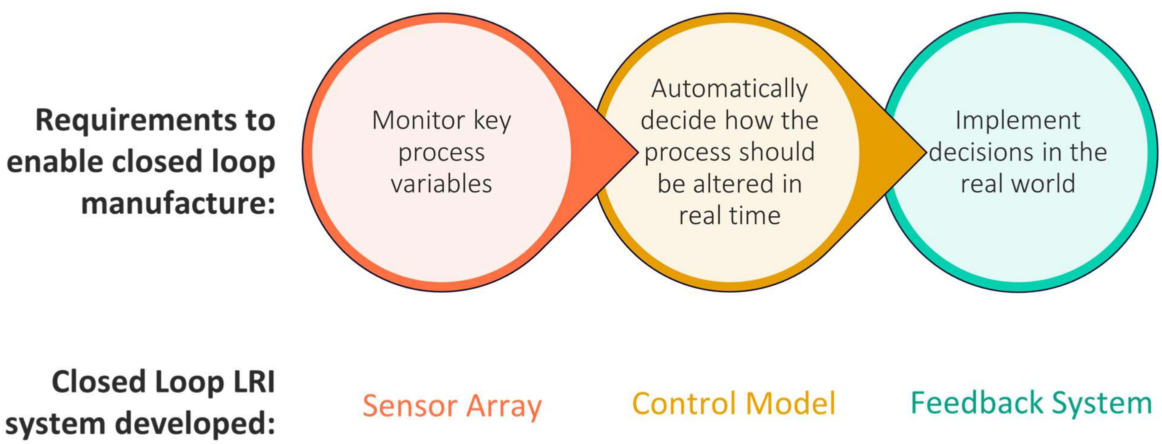

Figure 7 - Key main requirements for developing a closed loop manufacturing system

Overarching system requirements:

1. Monitor key LRI process variables
2. Decide how the LRI process should be altered in real time
3. Implement control decisions in the real world LRI process
4. Visualise real time data to the process operators
5. All elements of the system must communicate over 5G
6. The system must be easy to deploy anywhere in a factory with minimal rework (i.e. flexible)
7. The system must be able to manage an increase in the number of sensors or controllers easily (i.e. scalable)
8. The system must operate safety

Sub-system requirements:

1. **Sensor Array**
    1.1. Monitor LRI process variables in real-time, including:
        1.1.1. Resin flow (resin arrival status)
        1.1.2. Resin degree of cure
        1.1.3. Resin Tg
        1.1.4. Resin viscosity
        1.1.5. Part temperature
    1.2. Collect real-time resin injection machine process data
    1.3. Send all process data to the Control Model and Data Visualisation systems via 5G
2. **Control Model**
    2.1. Receive process data from Sensor Array and decide optimal time to closes resin outlet valves
    2.2. Send control commands to Feedback System
    2.3. Communicate with Sensor Array and Feedback System via 5G
3. **Feedback System**
    3.1. Receive control commands over 5G
    3.2. Control the resin outlet valves of the LRI process
    3.3. Manual override functionality in case of control model or network failure
4. **Data Visualisation System**
    4.1. Show real-time view of LRI process data in a single view
    4.2. Generate post-manufacture part traceability report automatically
    4.3. Store process data and make it accessible

USE CASE DEVELOPMENT AND INVESTIGATION

Use Case Architecture

As mentioned in the Introduction, two separate architectures were designed for the Closed Loop LRI system:

1. Closed Loop Control System Architecture
2. Data Visualisation System Architecture

These architectures reflect the different needs of the two systems. An on-premises design was used for the Closed Loop Control System as it required low-latency and high reliability for data flows. Running the system on-premises meant all data stayed within the building and data flows could be assured.

In parallel to this, the Data Visualisation System utilised a cloud-based architecture. As this system was not being used for control, and real-time latency was not as critical, using the cloud was preferred.

A top-level view of when to use cloud or on-premises solutions for digital manufacturing applications (such as closed loop manufacture) is shown in Table 1.

Table 1 - Benefits, limitations, and ideal use situations for on-premises or cloud solutions

	On-Premises	Cloud
Benefits	• Simpler to guarantee latencies • Easier to ensure robust data flows • Data security (data does not leave the building)	• Comes out cheaper overall • Many readymade tools for data capture and analysis • Easier to create a solution quickly • Highly scalable
Limitations	• More difficult to scale if systems expand • Hardware needs to be managed internally or through a service contract	• Still requires some level of on-premises solution to send the data to the cloud • Data transfer reliability, latency, and speed only as good as your internet connection (which may not be in your control)
Ideal use	• Situations where data flow speeds, latencies, and robustness are critical (e.g. closed loop control) • Safety critical situations (e.g. automation)	• Situations where you are using data for anything other than real-time control and feedback (e.g. data reporting for finished parts)

Closed Loop Control System Architecture

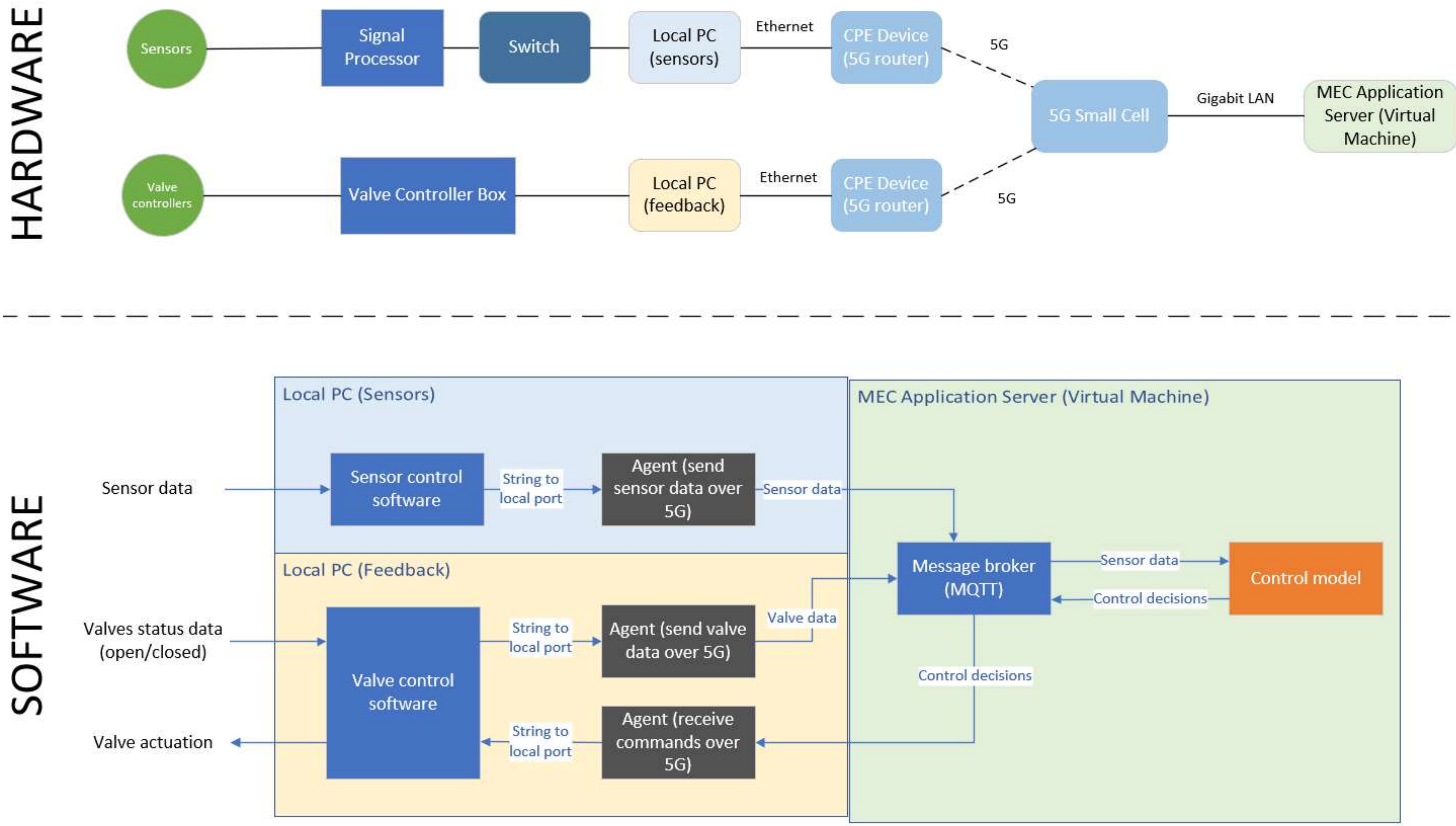

Figure 8 - Closed Loop Control System Architecture diagram

Closed Loop Control System Description

The control element of the Closed Loop LRI system was designed with three primary sub-systems: **Sensor Array**, **Control Model**, and **Feedback System.** The sub-systems and their interaction with one another are shown in Figure 9, whilst the full architecture of the system can be seen in Figure 8. The upper part of Figure 8 shows the hardware elements of the system and the lower part shows the software that is running on the hardware elements (Local PC (Sensors), Local PC (Feedback), and MEC Application Server (Virtual Machine)). The flow of sensor data, valve data, and control decisions can also be seen in Figure 8.

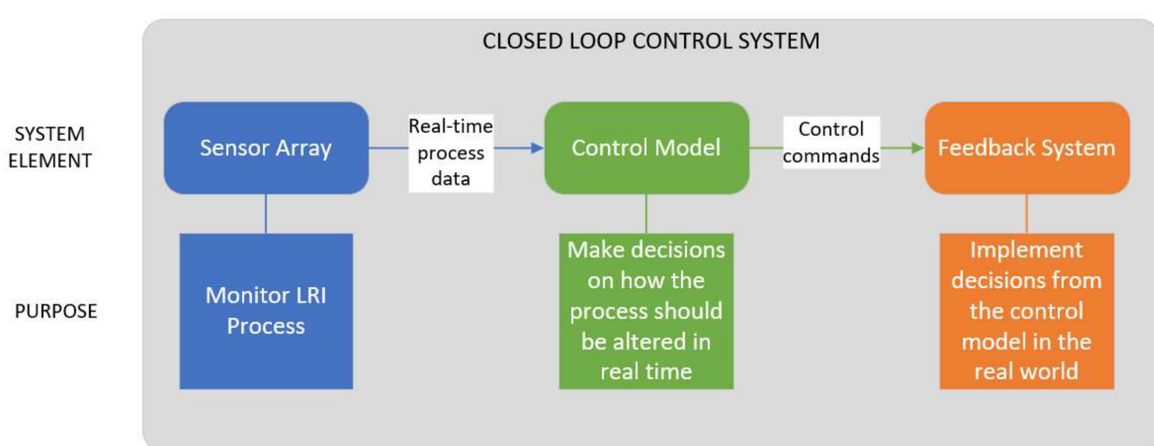

Figure 9 - Control system elements and flow of data within system

Sensor Array – The Sensor Array was developed to monitor numerous critical variables in the LRI process, however for the purpose of the control system only one parameter was of interest – resin arrival status. The location of the resin as it flowed through the part was monitored using resin arrival sensors (these 'trigger' when resin is in contact with them). The sensors were used to detect resin flow as it reached the outlet pipes, and this data was passed onto the Control Model.

Feedback System – The Feedback System was designed to automatically open or close the outlet lines of the infusion set up. This was performed using bespoke valves actuators that could be controlled remotely by the control model. The Feedback System had no intelligence (i.e. it did not know when valves should be open/closed) – it relied on the Control Model for commands.

Control Model – The Control Model received the resin arrival status data from the sensor array and then made decisions as to when the outlet lines of the infusion should be opened or closed. The Control Model sent its commands to the feedback system for implementation.

5G - The Control Model was run on a virtual machine on the MEC Application Server. This server is the ‘edge compute’ element of the 5G network and allows computational models to be run at a location in the network that is close to the data acquisition and feedback elements of a system. This ensures a low latency communication between the Sensor Array/Feedback System and the Control Model, which is critical for closed loop control. The Sensor Array and the Feedback System were connected to the 5G network using 5G routers (also known as CPE devices). All sensor data and control decisions were sent over the 5G network.

Full details of the Infusion Setup, Sensor Array, Control Model, and Feedback System can be found in their respective sections in Use Case Development.

Data Visualisation System Architecture

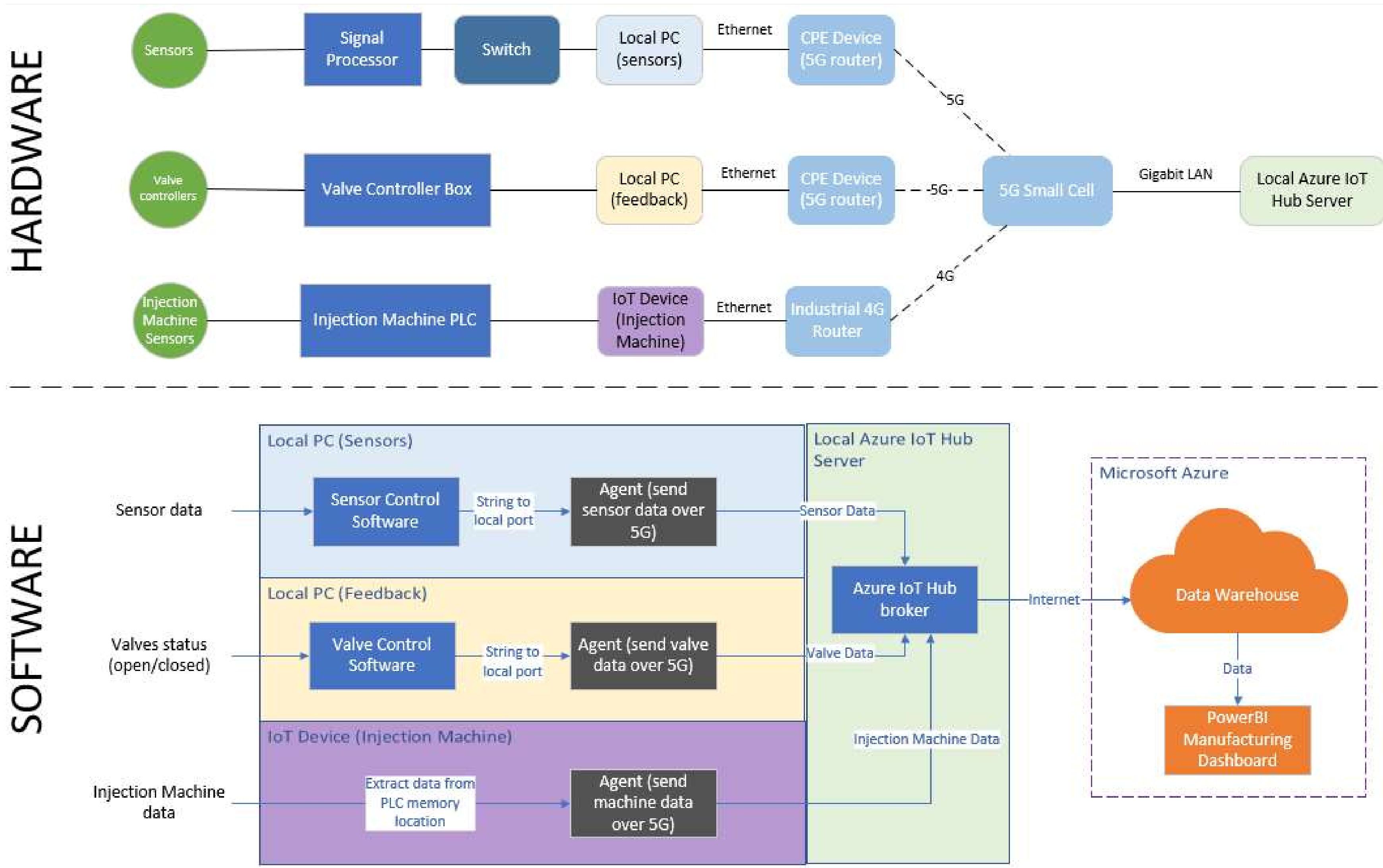

Figure 10 – Data Visualisation System Architecture diagram

Data Visualisation System Description

The Data Visualisation System took the data collected during the manufacturing process and displayed it in real-time on live dashboards. There were three main sources of data collected during manufacturing:

- **Sensor Array** – this collected data on the state of the part including resin characteristics (resin arrival status, degree of cure, Tg, viscosity) and temperatures.
- **Feedback System** – this collected data on the status (either opened or closed) of the automated valves in the feedback system.
- **Injection Machine** – this collected all key data from the resin injection machine, such as temperatures, pressures, and weights.

This data was sent to the systems Microsoft Azure cloud platform, where it was processed into the data warehouse. The data from the warehouse was then visualised on three different dashboards:

1. **Resin Monitoring (Live)** – this real-time dashboard displayed all the information on the state of the part, including resin characteristics and the valve open/close status.
2. **Injection Machine (Live)** – this real-time dashboard displayed all the key information from the resin injection machine.
3. **Part Report** – this report dashboard gave an overview of all the data collected during the manufacturing process. When the manufacture was complete, the data was instantly collated into a single easy to read report that could be interrogated and used to make data driven decisions to further improve the manufacturing process.

All three dashboards were **viewable from anywhere in the world** thanks to the use of the cloud platform.

Visualisation System Purpose

The purpose of the dashboards was to give LRI engineers greater insight into what was happening in the process in both real-time and post-manufacture. Gathering and displaying data pertinent to the process allows operators to make informed decisions about how the process should be changed in real-time to improve the part quality. Further, the ability to interrogate process data after manufacture helps engineers understand if the part has been made to the required quality and lets them assess how the process might be improved (e.g. by reducing cost, manufacture time, or improve part quality).

Additionally, the real-time data collection of key processing variables allows other elements of the LRI process to be controlled automatically in the future. Though only outlet valves are being controlled by the Closed Loop LRI system at present, items such as oven temperature control through degree of cure monitoring could be integrated in the future with relative ease as degree of cure is already being collected in real-time by the Data Visualisation System.

Finally, acquiring data on each part manufactured creates real-world data sets. These data sets can be used to train AI models in the future which will be able to control even more of the LRI process automatically.

Full details of this system can be found in the Data Visualisation System section under Use Case Development.

Use Case Development

Infusion Setup

The infusion setup consisted of three main elements: vacuum bag & tool, injection machine, and oven. The purpose of each element has been outlined in the LRI Manufacturing Equipment section, and the equipment used is the same as those shown in Figure 2, Figure 3, and Figure 4.

A silicone vacuum bag was used as it is reusable and more environmentally friendly than standard bagging material. Additionally, it is possible to embed sensors into a silicone bag (unlike a conventional bag), which ensures the sensors are in the same location on the part for every manufacture.

Figure 11 shows a diagram of the infusion set up. There was a single resin inlet and four isolated resin outlets. The resin enters the bag cavity at the inlet, fills the fibres, and flows through to one of the four outlets. The outlets continually draw vacuum on the part to keep the resin flow moving.

The details of part are shown in Table 2.

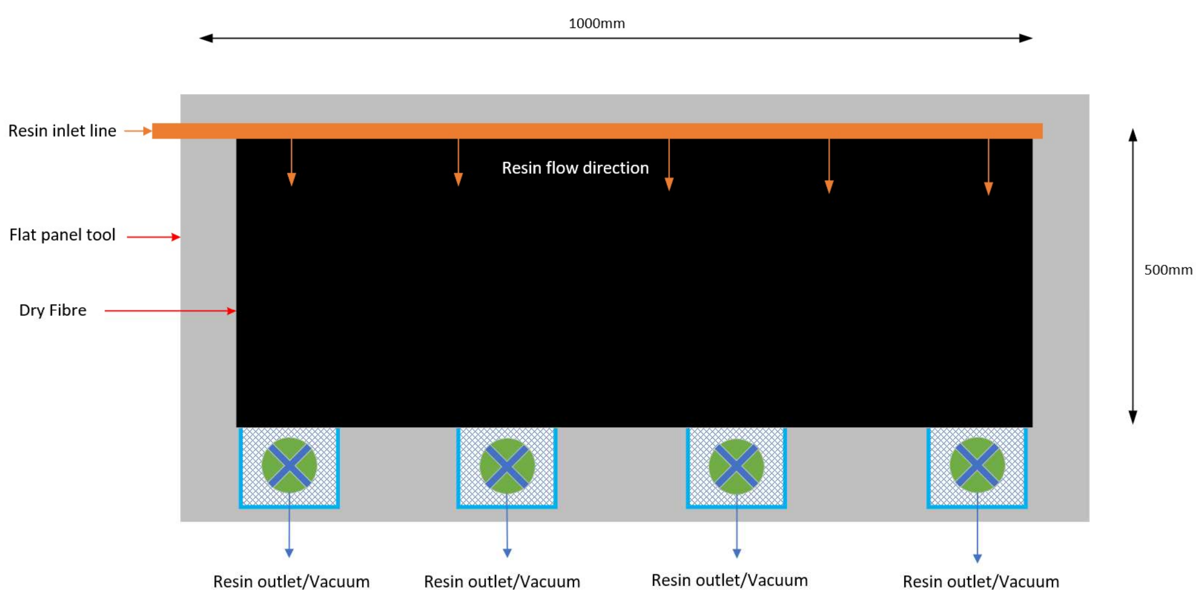

Figure 11 - Infusion set up diagram

Table 2 - Composite part details

Composite Type	Fibre	Fibre architecture	Resin	Size	Shape
Glass fibre reinforced polymer (GFRP)	Glass fibre	Plain weave	Hexcel RTM-6 epoxy (one part)	1 x 0.5 m	Flat panel

Sensor Array

The Sensor Array consisted of seven sensors in total:

- 4x In-line resin arrival sensors
- 3x In-bag resin cure monitoring sensors

All sensors were supplied by Synthesites Ltd[3], Greece.

In-line resin arrival sensors – These sensors are hollow tubes that are designed to fit within the pipework of an infusion set up, or 'in-line'. They are piezoresistive sensors, meaning they detect changes in resistance and use this to determine if resin is in contact with the sensor. The sensors are initialised as 'off' or 'resin not arrived', and when resin reaches the sensor they would switch to 'on' or 'resin arrived' (i.e. they are Boolean sensors). The Sensor Array had one resin arrival sensor at each of the four resin outlets – this enabled the Array to detect when resin reached each outlet separately. Images of the sensors are shown in Figure 12 below.

[3] https://www.synthesites.com

Figure 12 - In-line resin arrival sensor (left), sensor in place within infusion set up (right)

In-bag resin cure monitoring sensors – These sensors were disk-shaped and designed to be in contact with the part during the LRI process. They too were piezoresistive sensors, and they could monitor a wide array of resin characteristics in real-time:

- Resin arrival status
- Degree of cure (DoC)
- Glass transition temperature (Tg)
- Viscosity
- Temperature

The sensors 'activated' when resin contacted them. The sensors themselves monitored only resistance and temperature directly, however the Synthesites Sensor Control software converted these measurements into resin arrival status, DoC, Tg, and resin viscosity in real-time. The sensors were integrated into the silicone bag to enable them to be in direct contact with the part during manufacture. The sensors and bag integration are shown below in Figure 13.

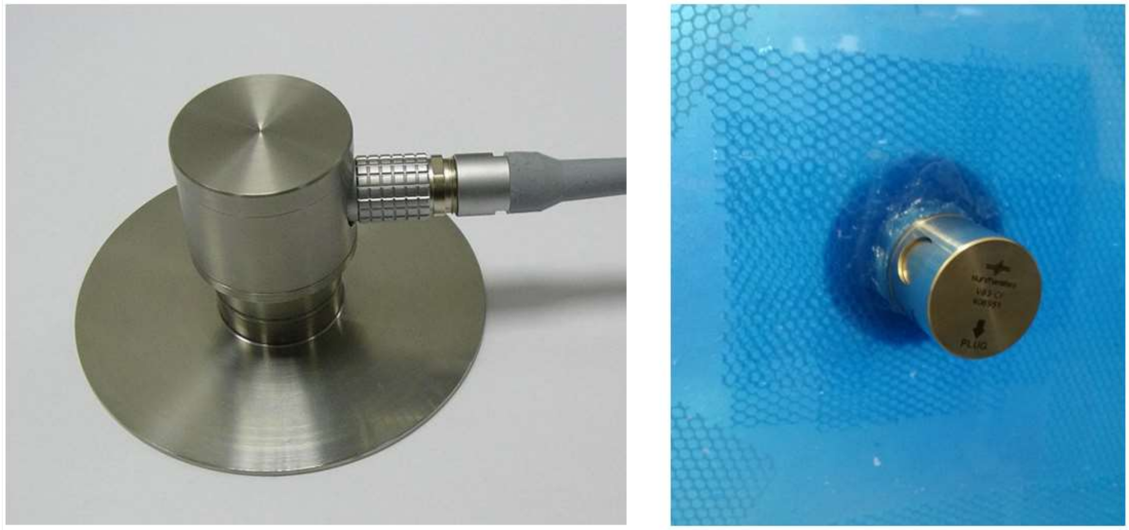

Figure 13 – In-bag resin cure monitoring sensor (left), and sensor integrated into a silicone bag (right)

The arrangement of the sensors in the Sensor Array within the LRI set up is shown in Figure 14 and Figure 15.

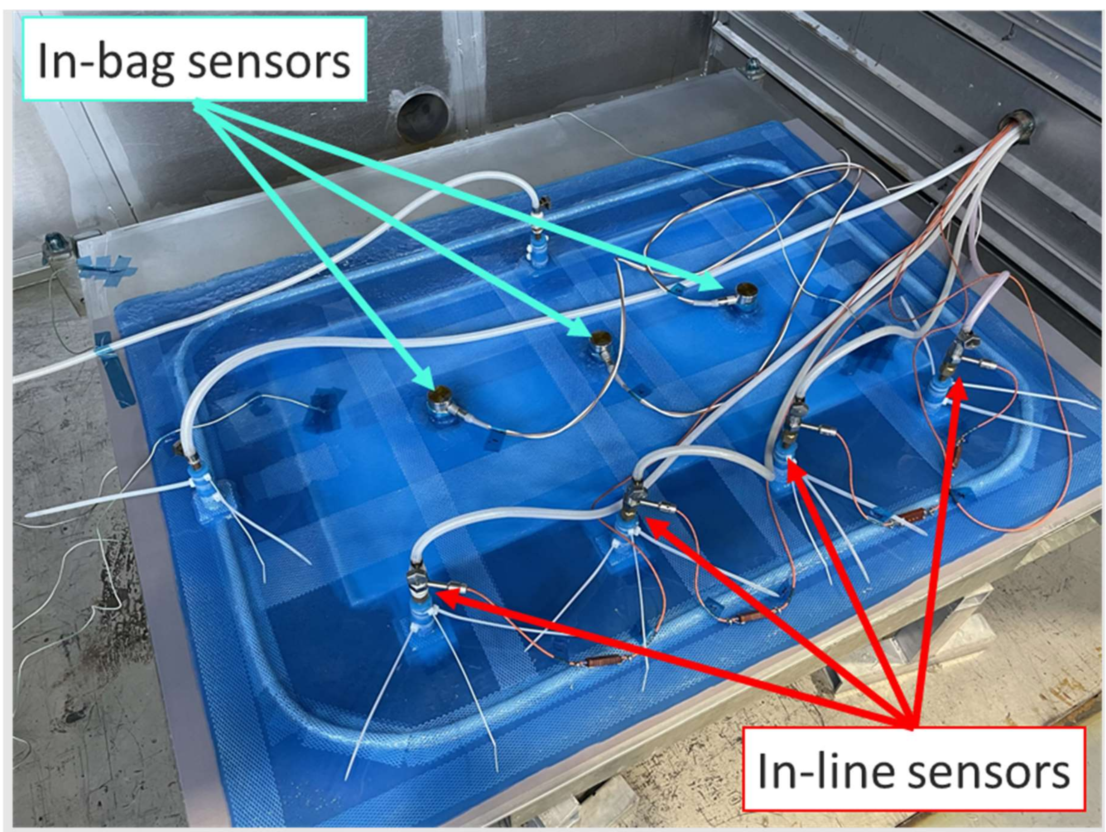

Figure 14 - Image of Sensor Array in the LRI manufacture setup

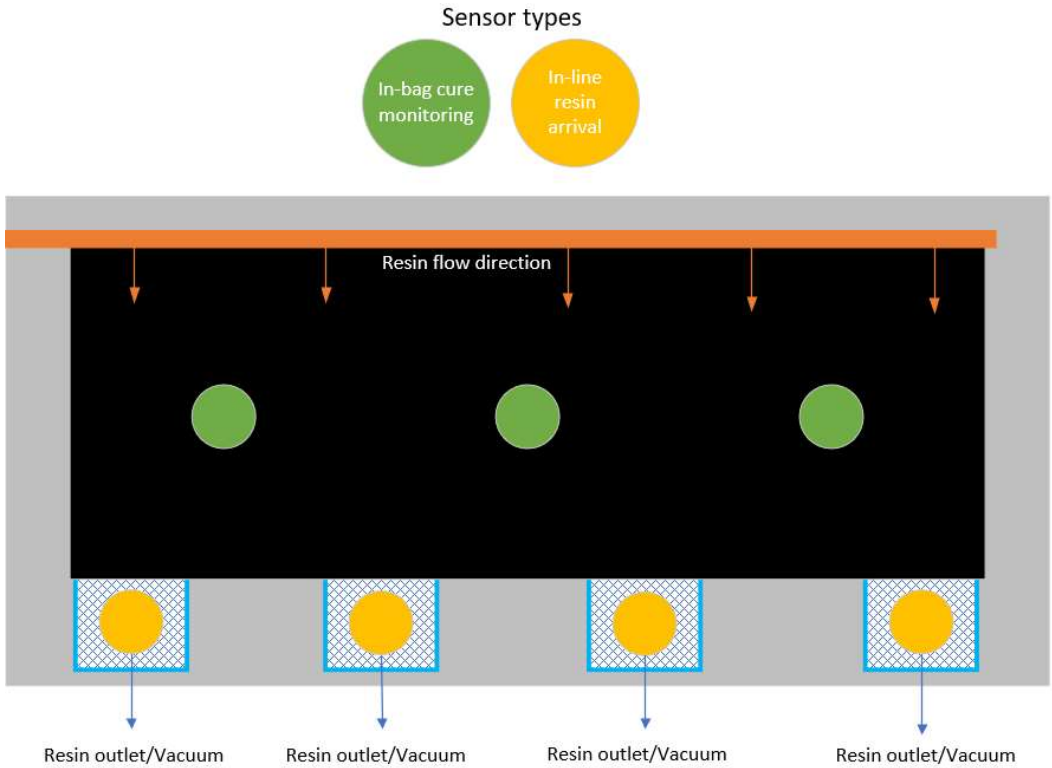

Figure 15 - Diagram of sensors in the Sensor Array

Additional elements of the Sensor Array (highlighted in the architectures in Figure 8 and Figure 10) are as follows:

- **Local PC (Sensors)** – Hosted the Sensor Control Software and Sensor Agent
- **Sensor Control Software** – This was a combination of two software products from Synthesites Ltd: OptiVIEW, and ORS. The software managed the sensors and made the sensor data available to 3rd party applications (i.e. Sensor Agent) via local ports.
- **Sensor Agent** – A custom build Python script that collected the sensor data from the Sensor Control Software, converted it into an MQTT message format, and sent it to the Control Model and the Azure IoT Hub Broker.
- **CPE Device (5G Router)** – this connected the Sensor PC (and thereby Sensor Array) to the NCCs 5G network, allowing the Sensor Agent to send the data over the network. The router used was an AirSpot 5G CPE from Airspan – this is shown in Figure 16.

Figure 16 – AirSpot 5G CPE

Injection Machine Connectivity

The injection machine used for the LRI manufacture was a CIJECT 6 Resin injection machine from Composite Integration, UK[4]. The machine already had sensors recording numerous variables important to the LRI manufacturing process, however the data was kept locally within the machine. To be able to extract the machines manufacturing data in real-time and send it to the Data Visualisation System, a custom system was developed and integrated into the machine's electrical cabinet. There were two primary elements: an IoT device, and a router. The architecture of these devices can be seen in Figure 10.

IoT Device – The device used was a Hilscher netIOT Edge Gateway (NIOT-E-TPI51-EN-RE), essentially a small, industrialised computer similar to a Raspberry Pi. The device was connected (via ethernet) to the injection machines' PLC. A custom developed node-red script running on the IoT device extracted the real-time machine data from the PLC, converted it into an MQTT message format and sent it to the Azure IoT Hub Broker. The data being live streamed from the injection machine included:

- Resin temperature
- Resin weight
- Resin pot pressure
- Various pot temperatures including:
  - Resin pot air temperature

[4] https://composite-integration.co.uk

  - Resin pot heater plate temperature
  - Resin pot heater belt temperature
- Injection hose temperature

Router – The IoT device had to be connected to the manufacturing network for it to be able to send the machine data (in MQTT message format) to the Broker. To facilitate this connection an industrial 4G router (Siemens SCALANCE E M876-4) was used. The router was placed into the machine cabinet and connected via ethernet to the IoT device. High gain 4G antennas were fixed to the machine to provide network signal to the router. A 5G router was not used in this instance as no DIN-rail mountable industrial 5G routers capable of working on a 5G SA network were available on the market.

The machine itself can be seen in Figure 4, while Figure 17 shows the IoT Device and the Router integrated into the machine cabinet.

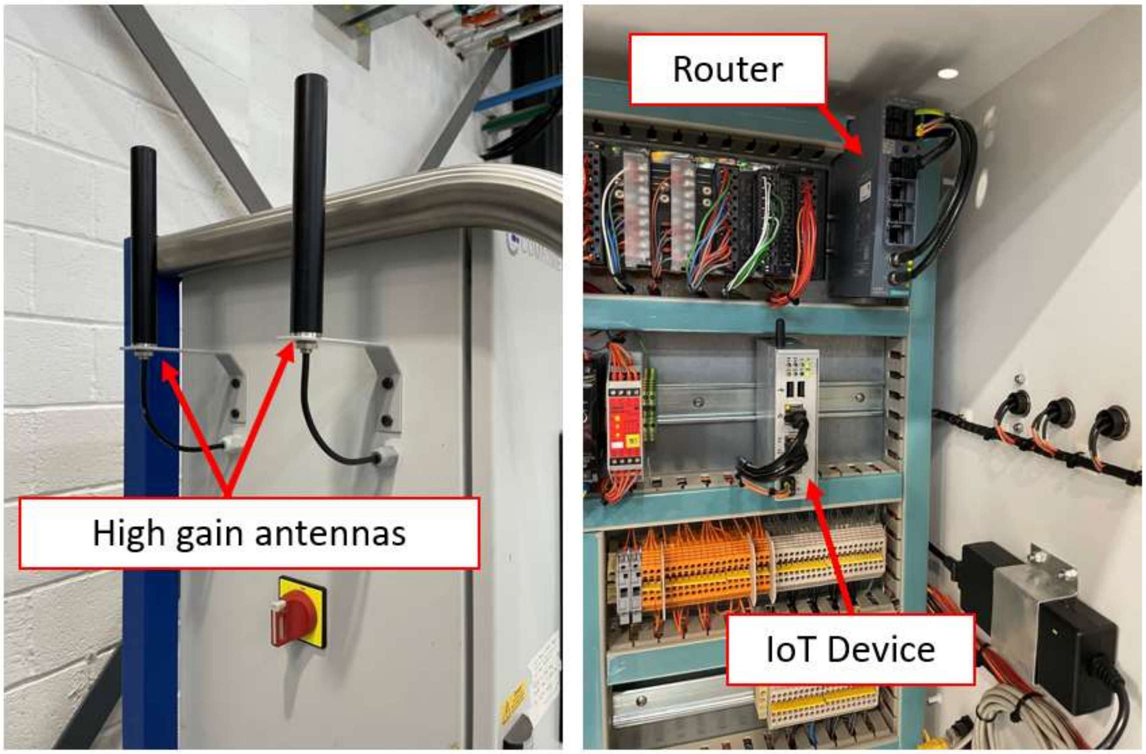

Figure 17 - IoT Device and 4G Router integrated into injection machine

Control Model

The Control Model was hosted on a Windows 10 virtual machine running on the MEC Application Server, this can be seen in the architecture in Figure 8. The server was located on-premises in the NCC server room (as opposed to in the Cloud). The model was a custom developed Python script. It packaged its commands into an MQTT message format that could be read by the Agents in the Feedback System.

To be able to receive and send MQTT messages from and to the Sensor Array and Feedback System, an MQTT message broker was used; it was hosted on the same virtual machine as the Control Model. The broker used was the open source Mosquitto MQTT Broker[5] from the Eclipse Foundation. All sensor data/control commands sent between the Sensor Array, Feedback System, and Control Model were via the MQTT broker.

The Control Model operated as follows:

1. Start Control Model – command all valves to set to the 'open' position (default position).
2. Wait for resin arrival signal from the Sensor Array's In-line sensors located at each of the four resin outlets
3. When resin is detected at an outlet, the Control Model receives the message from the Sensor Array – the model begins a 60 second timer.
4. Once the 60 seconds is complete, a control command is sent to the Feedback System to close the valve on the pipe that resin was detected at.
5. The model repeats this process for each valve (as resin is detected) until all four valves are closed.
6. Stop Control Model.

As the part geometry was not complex, the model developed was relatively simple; it replicated technician logic. It was sufficient to control the infusion for this particular part however the model could be upgraded for more complex parts that require greater levels of intelligence to control their process towards a successful manufacture. This could involve advanced AI models that use real process data to continuously learn and optimise the infusion strategy based off the results of previous infusions. The architecture of the

[5] https://mosquitto.org/

Closed Loop LRI system is designed to enable any future control model to be 'plugged in' with relative ease.

Feedback System

The Feedback System automatically controlled the opening and closing of the four resin outlets based off the commands it received from the Control Model. The top-level architecture can be seen in Figure 8 while the detailed architecture of the system is shown in Figure 18.

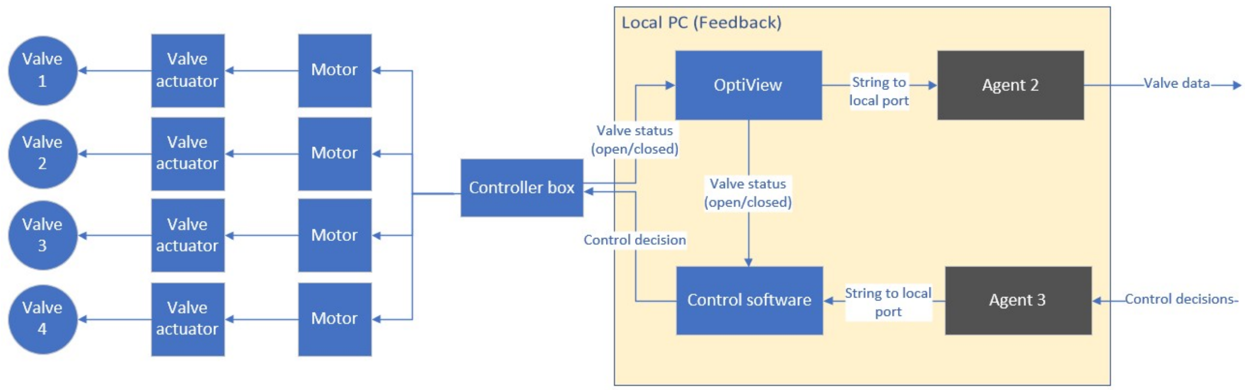

Figure 18 – Feedback System detailed architecture

The system consisted of several separate elements. These elements and their purpose are listed below:

Hardware

Figure 19 – Synthesites Controller box

Controller box – Synthesites product which the valve motors and valve relays plug into. The Controller box provides power to the motors to engage the Valve actuators and cause valve closure/opening. Upon completion of an opening or closure operation a valve status message is relayed back to the Controller box from the Valve actuator. The front of the box has 3 LED lights for each valve. 2 of the LEDs are used to indicate whether the connected valve is in the open or closed state. The other LED indicates when the motor is in operation. Each valve has 2 buttons on the front of the Controller box which enable manual opening (green button) and closure (red button). The Controller box was designed for safe operation with multiple fail safes. The emergency E-stop button kills all power to and from the box, whereas the PC deactivation button only kills communication between the box and the Feedback PC.

Figure 20 – Feedback PC (NUC)

Feedback PC (NUC) – An industrial minicomputer that facilitates hosting Feedback Agents 2 and 3, the Synthesites Control software and Synthesites OptiView software. The Feedback PC facilitates the interfaces between multiple pieces of software. The interface between Feedback Agent 3 and the Control software, the interface between the Control software and OptiView, and the interface between OptiView and Feedback Agent 2 are all facilitated by the Feedback PC. The Feedback PC is physically connected to the Controller box and AirSpot 5G CPE device via ethernet.

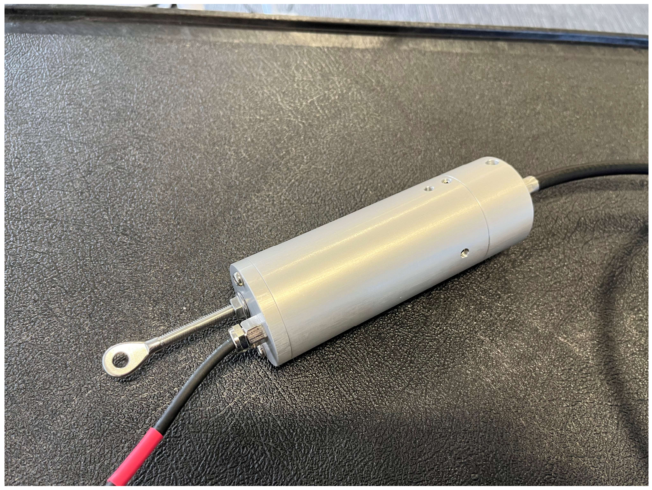

Figure 21 – Valve motor

Valve motors – Electric motors that provide the physical force required to open and close valves. The motors have power supplied by the Controller box and are each connected to a Valve actuator.

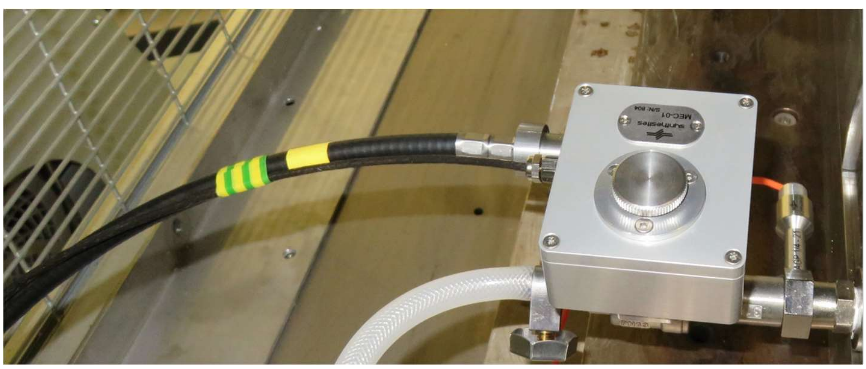

Figure 22 – Valve actuator

Valve actuators – The physical element that sits on top of the ball valve to physically implement opening and closing of vent valves. The connection between actuators and their designated motor is achieved with 2 metallic cables housed within a single thick black cable housing. When power is supplied to a motor, force is applied to one of these metallic cables, rotating the ball valve and resulting in opening or closure.

AirSpot 5G CPE – Wireless 5G router used to connect the Feedback PC (and thereby the Feedback System) to the NCCs 5G network. This router was the same type as that used in the Sensor Array and is shown in Figure 16.

Software

There are 4 main software elements to the feedback system. Some software was developed by Synthesites (Control software and OptiView) and some by the NCC (Feedback Agent 2 and Agent 3).

Control software – Synthesites software set up to receive open/close signals from Agent 3 via local ports. The Control software then transmits these signals to be implemented by the Controller box. The Control software also receives the current physical state of the valves (open/closed) from the OptiView software running locally on the Feedback PC.

OptiView software – Synthesites software that relays valve status messages to Agent 2 and the Control software.

Feedback Agent 2 – JavaScript developed within Node-RED. Agent 2 effectively initialises the valve statuses, then relays any updates to the valve statuses onwards to the Azure IoT Hub broker (see Figure 10 for system architecture details). The following operations are executed in sequence:

- The state of each valve is initialised and set to "open" – this message is sent to the Azure IoT Hub broker for the Data Visualisation System.
- Agent 2 connects to OptiView and receives any change in valve status from it.
- When a valve status changes Agent 2 sends the change in a message to the Azure IoT Hub broker for visualisation.

Feedback Agent 3 – JavaScript developed with Node-RED. Agent 3 effectively receives control messages from the Control Model (via the on-premises MQTT broker), then parses them to the Control software. The following operations are executed in sequence:

- Subscribes to on-premises MQTT broker (to listen for commands from the Control Model)
- Waits for a change-state command for any valve (e.g., Open → Close) then sends the message through to the Control software.
- If the last message sent through to the Control software hasn't been implemented, then Agent 3 creates a queue of messages ready to be sent one at a time once the previous message has been implemented by the feedback system.

Data Visualisation System

The Data Visualisation System was built using Microsoft Azure; the architecture can be seen in Figure 10. The three key elements to this were: **Azure IoT Hub**, **Data Warehouse**, and **Power BI Dashboards**.

Azure IoT Hub – The IoT Hub served as the gateway to the Cloud based Azure platform. It was hosted on premises on the NCCs servers. All data collected during manufacturing was sent to the IoT Hub over the 5G network, and the Hub then forwarded the data to the Azure data warehouse in the cloud (via the internet).

Data Warehouse – The warehouse was hosted in the cloud and served as the database for all manufacturing data. The database type used was SQL.

Power BI Dashboards – The Power BI application was also hosted in the Azure cloud and interfaced with the data warehouse to extract and display data in real-time on live dashboards, and on a post-manufacture report dashboard.

The two live real-time dashboards developed using Power BI were: **Resin Monitoring**, and **Injection Machine.** The resin monitoring dashboard displayed all the data collected by the Sensor Array, and the valve open/close status collected by the Feedback System. The injection machine dashboard displayed all the data collected by the Injection Machine Connectivity system. Real data displayed on each dashboard can be seen in Figure 26 and Figure 27.

The final dashboard developed was **Part Report** – this showed a one-page summary of the part manufacture. It contained all the data collected from the Sensor Array, Feedback System, and injection machine, displaying it in a simple and easy to digest report. Additionally, the manufacturing data was tagged with important metadata such as time of manufacture, part number, ambient conditions, names of individuals involved, and many others. It did this by tagging the metadata of the part to the incoming data from the manufacture. To do this a Microsoft Power App called 'LRI job control' was developed and is viewable in Figure 23.

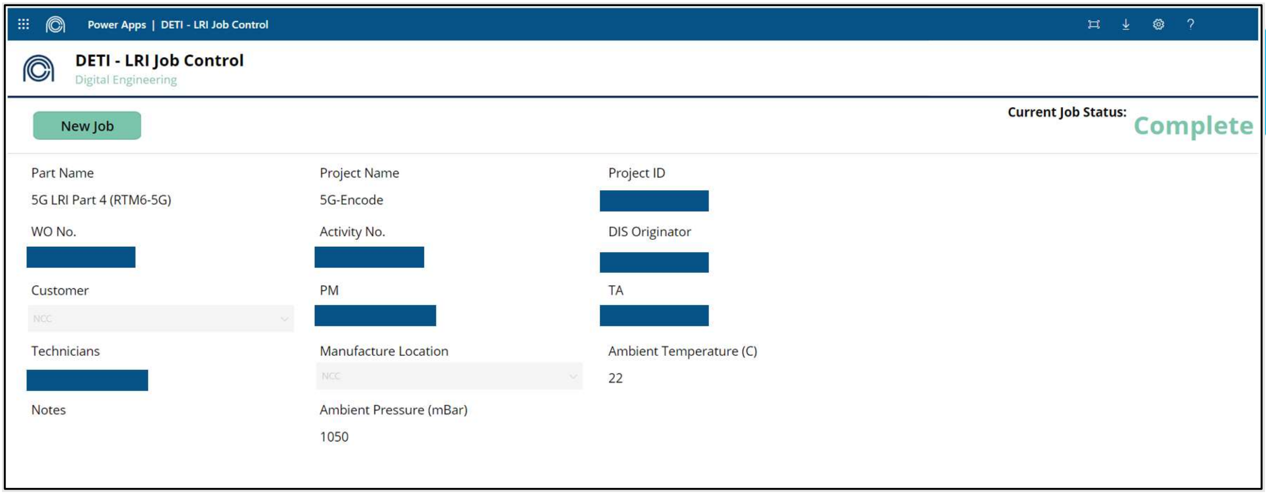

Figure 23 – LRI Job control application

The app had several fields that were filled in by the operator prior to part manufacture. The operator then used the app to 'start' and 'stop' the job – all live data collected between the 'start' and 'stop' was tagged with the metadata. The Part Report dashboard had a drop-down selector that could be used to easily switch between the reports of all the parts made using the Closed Loop LRI system.

This collection formed a comprehensive dataset on each part, giving engineers the ability to make informed data-driven decisions during and after manufacture. A Part Report generated during use case testing can be seen in Figure 28 under Data Visualisation System Results.

Use Case Testing

System Setup and Tests

The Closed Loop LRI system was deployed into the NCC factory – the set up can be seen in Figure 24 and Figure 25.

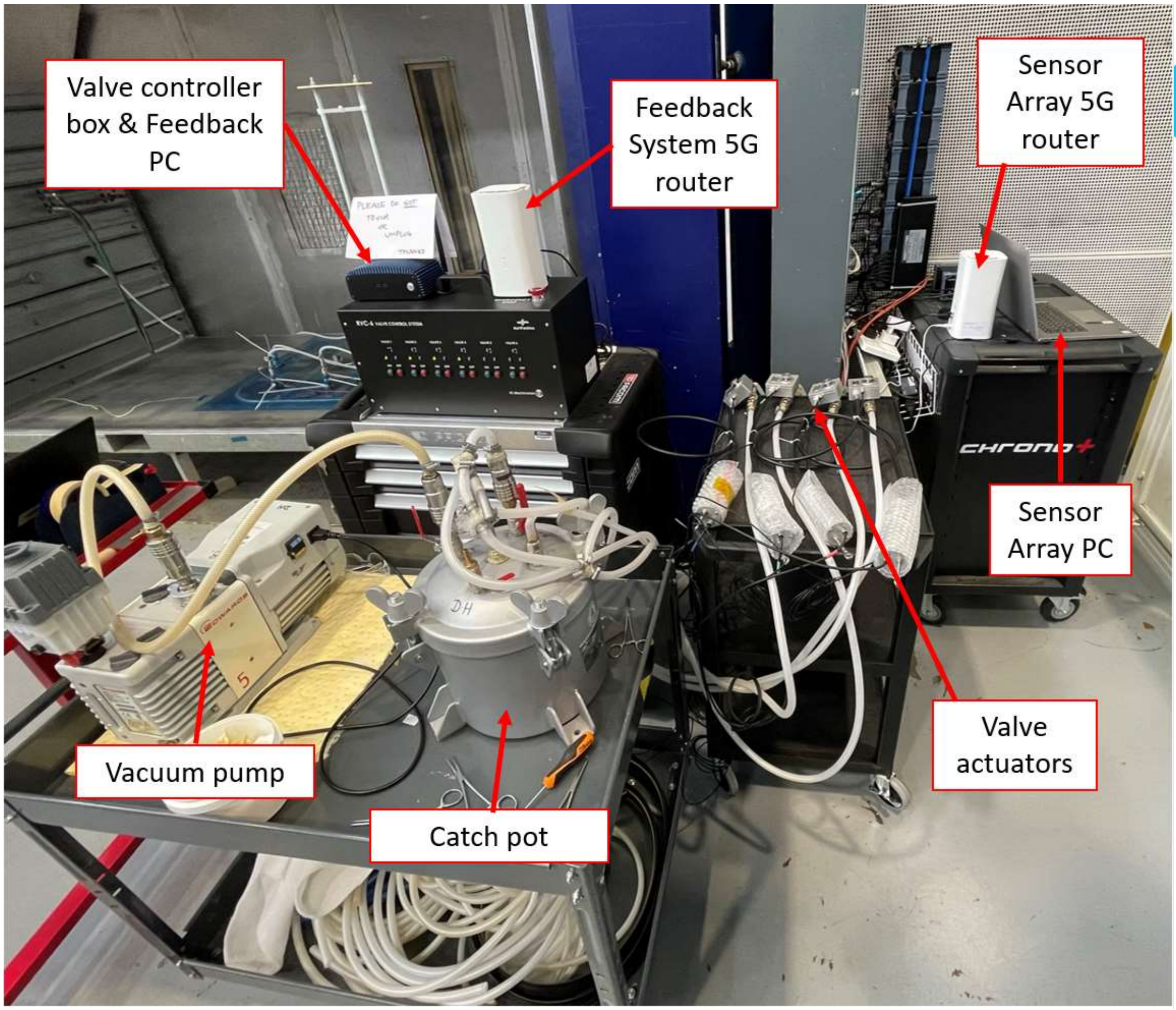

Figure 24 - Closed Loop LRI set up (outside the oven view). Catch pot and vacuum are used to pull vacuum on bag/part

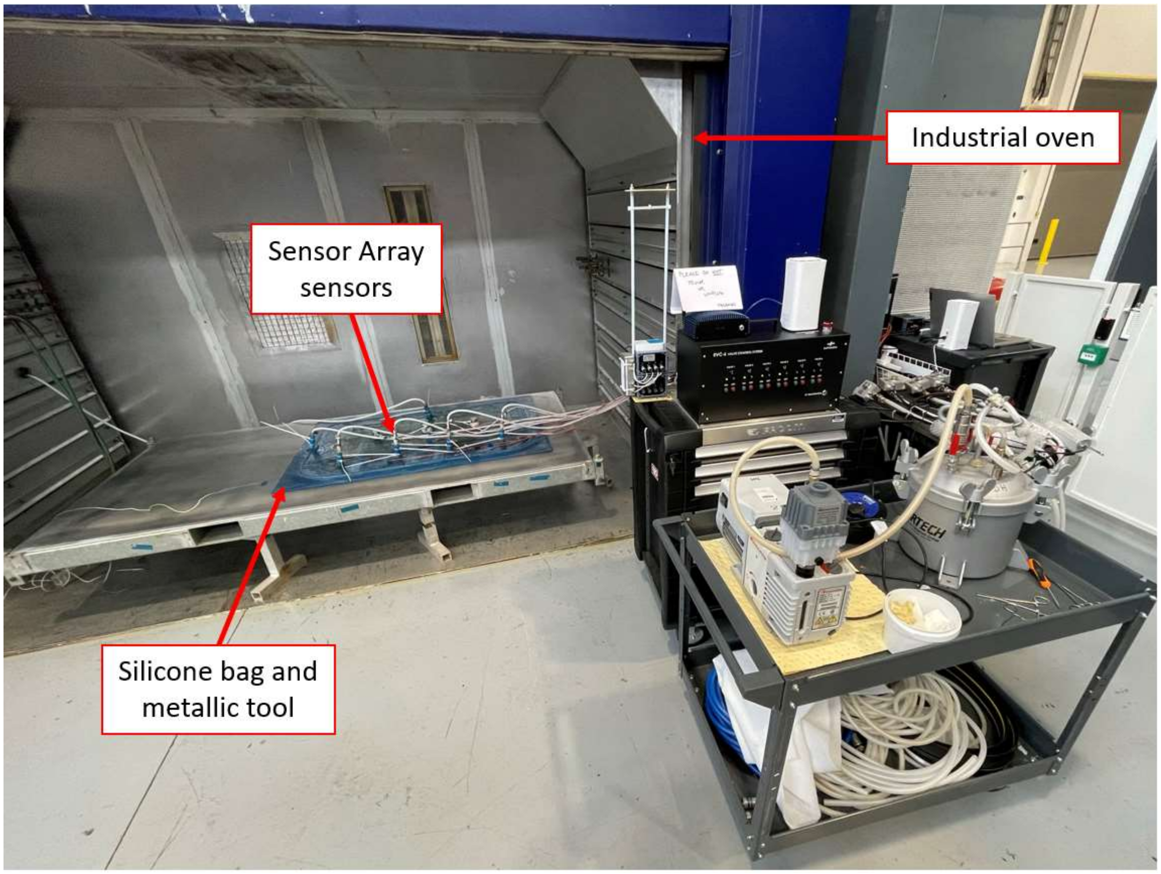

Figure 25 - Closed Loop LRI set up (inside oven view)

Three full manufacturing trials were performed with the Closed Loop LRI system, and their details are shown in Table 3. The trials were identical except for the network used to run them.

Table 3 - Table of manufacturing trials

Part No.	1	2	3
Network Used	4G	5G SA	Toshiba 5G NSA

Use Case Results

Closed Loop Control System Results

For all three trials the **Closed Loop Control system worked effectively**. The Sensor Array, Feedback System, and Control Model worked together as planned. As resin was detected by the In-line resin arrival sensors this information was sent over the network to the Control Model, and the control models' commands to close vents were successfully sent (over the network) and implemented by the Feedback System.

Some issues were experienced with the sensors in the Sensor Array, namely the In-line resin arrival sensors. For each trial performed one of the four sensors failed to trigger even when resin was in contact with the sensor. This meant that the Control Model did not close the sensors corresponding resin outlet valve correctly. These issues were likely due to faulty sensors.

Overall, this was a minor issue, and the system was considered a success.

Data Visualisation System Results

All elements of the **Data Visualisation System worked as planned and provided excellent insight into the manufacturing process**. The data collected by the Sensor Array, Feedback System, and injection machine was successfully streamed in real-time to the Azure cloud. Snapshots of the live dashboards can be seen in Figure 26 and Figure 27.

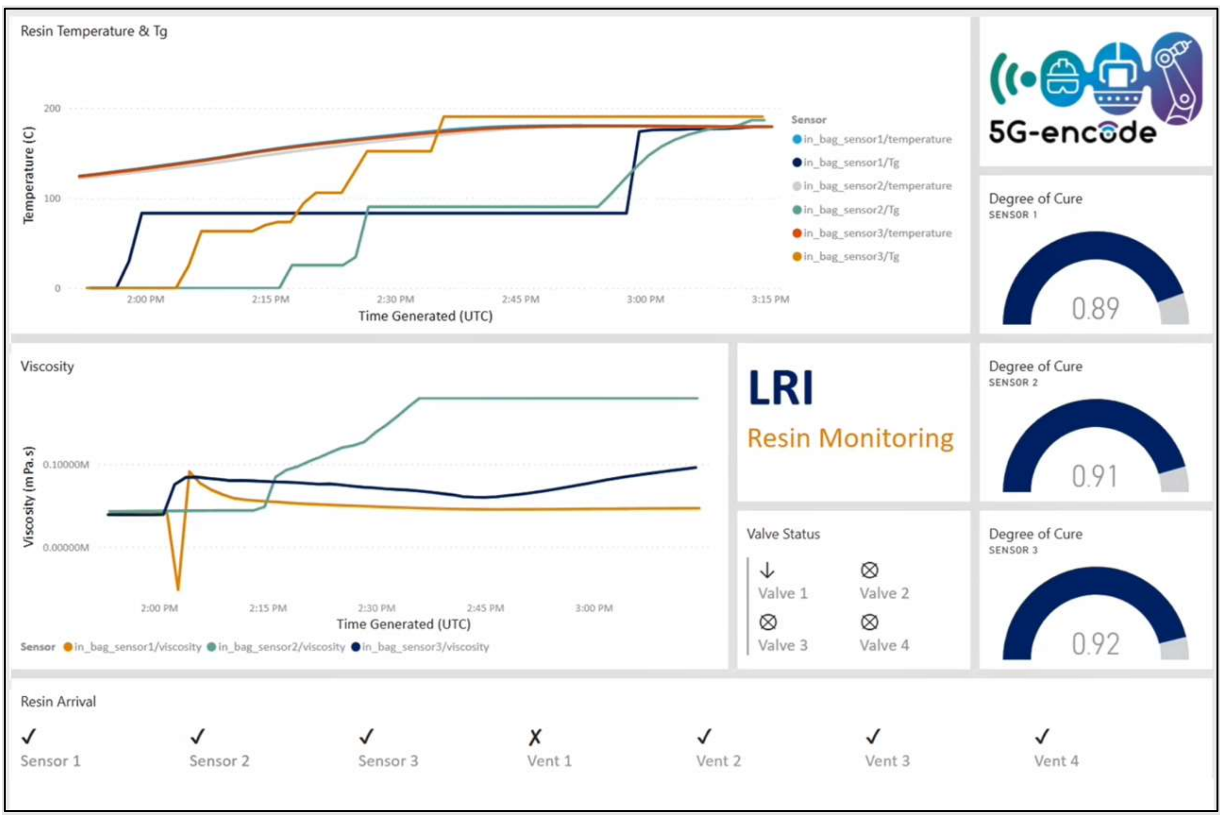

Figure 26 - Resin monitoring dashboard showing live manufacturing data

Figure 27 - Injection machine dashboard showing live data from the injection machine

The Part Report dashboard also worked as planned – the live data collected during manufacturing was successfully tagged with the part metadata, and all this information was displayed on the part report card. Figure 28 shows the data report from part number 1 (performed on 4G).

Figure 28 - Part Report dashboard showing the data for part number 1

During the trials it was noticed that the three In-bag cure monitoring sensors often gave differing readings during the initial part of the manufacture (infusion), however the sensor readings began to correlate in the cure phase. Use of an incorrect release agent for the sensors was the suspected cause of this issue.

Some stability issues with the Toshiba 5G NSA and NCC 5G SA network were experienced on parts 2 and 3 respectively. Network drop off resulted in a loss of data capture for the Data Visualisation System – this is explored in more detail in
5G Industrial Assessment.

Use Case Discussion

Use Case Benefits

The benefits realised by the Closed Loop LRI system are as follows:

Enhanced process insight – A far greater understanding of what is happening during the LRI process is possible with this system. To the authors knowledge, nothing currently exists in LRI manufacturing that can collate the data across the entire process (part, oven, injection machine) and feed this back in real-time to engineers on a single platform. At present, data is either not collected or stored locally on machines. At best equipment has vendor specific platforms that must be switched between to get a view of what is happening. The Closed Loop LRI system provides a single platform to view all process data cleanly, allowing data driven decisions to be made mid or post-manufacture to improve part quality or optimise the process. The total number of process variables monitored and displayed on the system is thirteen[6].

For the part made in this project, the data showed that the cure time could be halved and still give the same part quality. This optimised process is **cheaper**, allows for **higher oven utilisation**, and has **reduced the environmental impact** of the part manufacture.

Data capture flexibility – The system has been designed for flexibility, meaning it can be deployed onto any LRI manufacturing system in the NCC with relative ease (as data capture and control is all performed wirelessly over 5G). Additionally, the system is scalable, allowing new sensors or controllers to be added easily.

Manufacturing labour cost savings – The infusion element of the LRI process typically requires 2 operators, one to control the outlet valves and one to monitor the injection machine. The Closed Loop LRI system controls the valves automatically, meaning only one operator is required – this allows the other operator to work on more high-value activities.

[6] Resin parameters: temperature, Tg, degree of cure, resin arrival, viscosity, valve open/close status – Machine parameters: injection hose temperature, heater belt temperature, heater plate temperature, pot air temperature, pot resin temperature, pot weight, pot pressure.

Report generation cost savings – Creating a part data report often takes many hours or even days of work. Data from various sources like machines or dataloggers must be extracted, then collated into a spreadsheet. They then need time-syncing, and finally graphs can be generated. They are critical however in understand how the part was made. This activity is now done automatically and is available in near real time after part manufacture is finished.

An overview of these benefits and their value is shown in Table 4.

Table 4 - Table of benefits

Benefit	State prior to Closed Loop LRI system	State with Closed Loop LRI system	Value
Enhanced process insight	Minimal understanding of process (mid or post manufacture)	Detailed data, clearly displayed, allowing for data driven decision making	Part cure time has been halved due to enhanced process understanding (optimised process)
Data capture flexibility	Minimal flexibility in existing data capture systems	Highly flexible system – deployable on different LRI processes	All other benefits are not tied to a single LRI process, but achievable anywhere
Manufacturing labour cost savings	Two operators required for manufacture	Only one operator required	25% labour cost (1-hour time) saving per part [increases with increasing system complexity]
Report generation cost savings	One full engineers' day to generate report	Report generated automatically	100% cost (8-hour time) reduction per part

Specific monetary values for labour cost savings are dependent on labour rates – these vary between industry sectors. As an example, an industry with an engineers' charge rate of £80/hour would realise a cost saving of £640 per part by utilising the automatic report generation.

Use Case Limitations, Lessons Learnt, and Recommendations for Future Work

Limitations of the Use Case

Though significant advancements have been made through this use case in automating and giving greater insight into the LRI process, it is only the beginning. The opening and closing of outlets valves is a small part of the full LRI process - much of it remains manual.

The part made using this system was a flat panel, however there is a need to show the system working on a more realistic geometry, such as a plane wing. Additionally, the data collected on the part was not validated (e.g. degree of cure, Tg), meaning further analysis is required before the sensor data can be relied upon.

Significant further benefits could be realised if more process elements were controlled by the Closed Loop LRI system. Key next steps include:

- Automating the oven cure cycle using the degree of cure reading from the Sensor Array
- Automating the full injection process though control of the injection machine and inlet valves

Furthermore, the control model used was basic, employing only technician logic. This model was chosen as infusing a flat panel is relatively simple and did not require complex control; however, if the system is deployed to a complex part infusion, or if more process elements are to be controlled by the model, **a more intelligent (likely AI based) model would be needed**. A model of this kind could also facilitate continuous process optimisation by learning from the results of previous infusions. A Machine Learning approach to resin infusion has already been studied by the NCC and the Centre for Modelling and Simulation (CFMS), Bristol[7] and this type of model could be deployed into the Closed Loop LRI system.

[7] https://cfms.org.uk/news-events-opinions/news/2018/february/cfms-and-ncc-to-produce-digital-demonstration-of-machine-learning-in-composites-manufacturing/

If successful, these developments (among others) would lead to:

- Reduced part manufacture cost and time
- Automatic quality assurance (no need to conduct non-destructive testing or material analysis)
- Reduced environmental impact though:
  - Reduced equipment/energy use to make the same parts
  - Less scrap as parts made right every time

Lessons Learnt

Some of the key challenges overcome during the project included:

- Modifying a composite sensor system to work on a cellular network – the data from the sensors is typically used locally and had not been sent over a wireless 4G or 5G network before
- Streaming live data from a machine over a cellular network – the injection machine is a legacy piece of equipment and was not designed for this purpose
- Development of an architecture that can be used to enable any kind of closed loop manufacture (flexible and scalable)
- Enabling a valve control system to receive and execute commands remotely over a cellular network

Though successful there are some challenges still outstanding, these include:

- Sensor system and valve system still have a significant number of cables, this needs to be reduced to make the system more viable for use in industry
- The data streaming from the injection machine is not robust enough and needs further investigation to ensure it works every time

Use Case Conclusions

The aim of the Closed Loop LRI use case was to begin the process of automating the LRI manufacturing technique through use of 5G and other digital technologies. Additionally, it sought to bring greater insight into the process through data capture and visualisation. These aims have been achieved and have resulted in the development of an industry leading digital LRI system. The benefits realised including reduced manufacturing costs & times, along with greater insight into part quality, are in line with the benefits expected from a system of this kind (described in Project Objectives).

Future work is required to scale up the system, control more elements of the process, and apply the use case to more real-world part geometries; doing so will reap benefits far beyond the scope of this project. The system however has been designed for scalability and flexibility, meaning it is ready for future expansion.

5G INDUSTRIAL ASSESSMENT

All manufacturing trials performed were identical except for the network used to run the trials on. This section assesses the performance of the use case on the 4G, 5G SA, and Toshiba 5G NSA networks. The methodology for this is outlined in Introduction: Assessment Methodology.

4G Discussion

4G Test Setup

For the 4G trial the router of choice was the Siemens SCALANCE E M876-4 (pictured in Figure 29). This connected the Sensor Array and Feedback system to the Control Model and can be seen in use in Figure 30.

Figure 29 - Siemens SCALANCE E M876-4 4G router[8]

[8] https://support.industry.siemens.com/cs/document/109480265/delivery-release-of-scalance-m876-4-mobile-wireless-router?dti=0&lc=en-CA

Figure 30 - 4G router (with antennas attached) in operation

4G Results and Assessment

Latency between the Sensor Array/Feedback System and the Control Model virtual machine was assessed by performing pings. 100 ping requests were sent, and the statistics are shown in Table 5.

Table 5 - Ping statistics for the 4G network. Collected by sending 100 pings from the Sensor Array/Feedback System to the Control Model

		Ping round trip time (ms)		
Network	**Packet Loss (%)**	**Average**	**Maximum**	**Minimum**
4G	0	81	138	28

Overall, the Closed Loop LRI system performed well using 4G. The network appeared robust and stable, and worked well in the industrial environment. No data loss was recorded in the Data Visualisation System, and the Closed Loop Control System worked effectively.

Some radio signal black spots were noticed in the facility, meaning this could restrict the ability to deploy the Closed Loop LRI system in different areas. However, this issue could be easily rectified by relocating current radio cells or adding more in areas with poor signal coverage.

It is likely the system worked well on 4G as the number of sensors and controllers used was relatively low. The system was a proof of concept; stress testing the network with 10s-100s sensors/controllers was not in scope. However, one of the key requirements for a closed loop control system (as outlined in Introduction: Why 5G?) is low latency and high reliability. The latency seen over 4G was around 81ms, which is sufficient for the system currently; however, if the system was developed to include control of pressurised injections this latency may not be adequate. Pressure can change rapidly in an injection, so sensor data and commands need to be sent quickly to ensure accurate control and maintain safety.

Safety is also the driving factor for reliability, as if the control model can't communicate with the real-world control system temporarily this is a major issue. The reliability of the 4G network appeared sufficient, however this must be tested over a much longer period before it can be properly verified.

5G Discussion

5G Test Setup

For the 5G trials Airspan AirSpot 5G routers were used (shown in Figure 16). Their set up within the Closed Loop LRI system can be seen in Figure 24. Two routers were used, one each for the Sensor Array and the Feedback System. These provided the connection for both systems to the Control Model virtual machine.

5G Results

As with 4G, latency between the Sensor Array/Feedback System and the Control Model virtual machine over 5G was assessed by performing pings. The statistics are shown in Table 6, and the 4G statistics are also shown for ease of comparison.

Table 6 - Ping statistics for the 5G and 4G networks. Collected by sending 100 pings from the Sensor Array/Feedback System to the Control Model

		Ping round trip time (ms)		
Network	**Packet Loss (%)**	**Average**	**Maximum**	**Minimum**
4G	0	81	138	28
5G SA	0	33	47	17

Network statistics generated by the Accedian[9] Skylight Analytics system are viewable in Figure 31, Figure 32, and Figure 33. This system sat on the core switch in the 5G network and was able to monitor all data sent over the network. What is immediately noticeable in these figures is that the Closed Loop LRI system lost connection to the 5G network on numerous occasions. A major outage happened between around 15:00 and 16:00, while smaller outages occurred at around 16:20, 17:20, and 17:30. This outage caused significant issues and their effects are detailed in 5G Assessment. The cause of the outage was the 5G routers losing connection to the network. The outages resulted in a **network reliability rating of 85.6%** (as defined in Network Metrics).

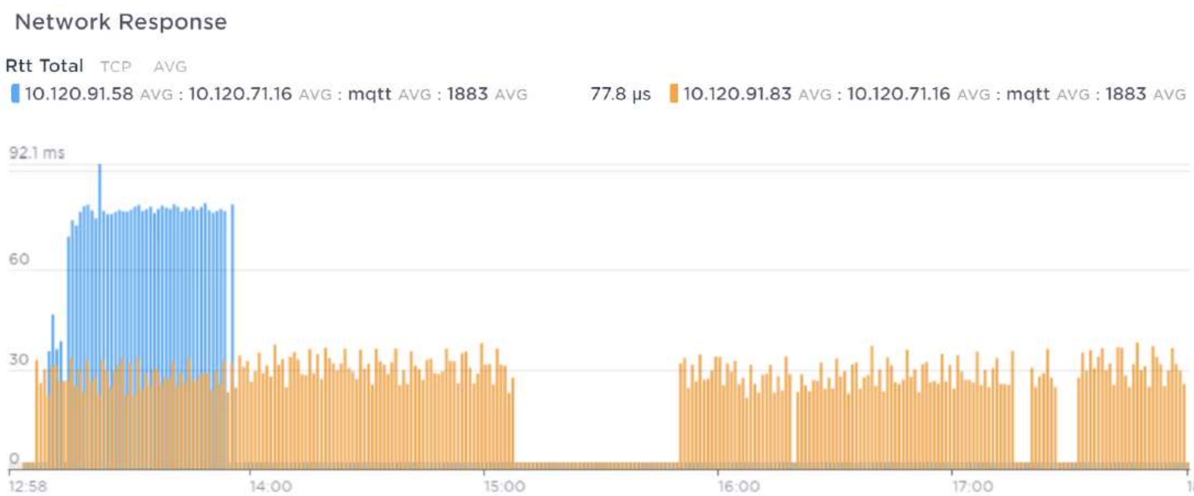

Figure 31 - Latency for data packets sent between Sensor Array (orange bars) and Feedback System (blue bars) to Control Model

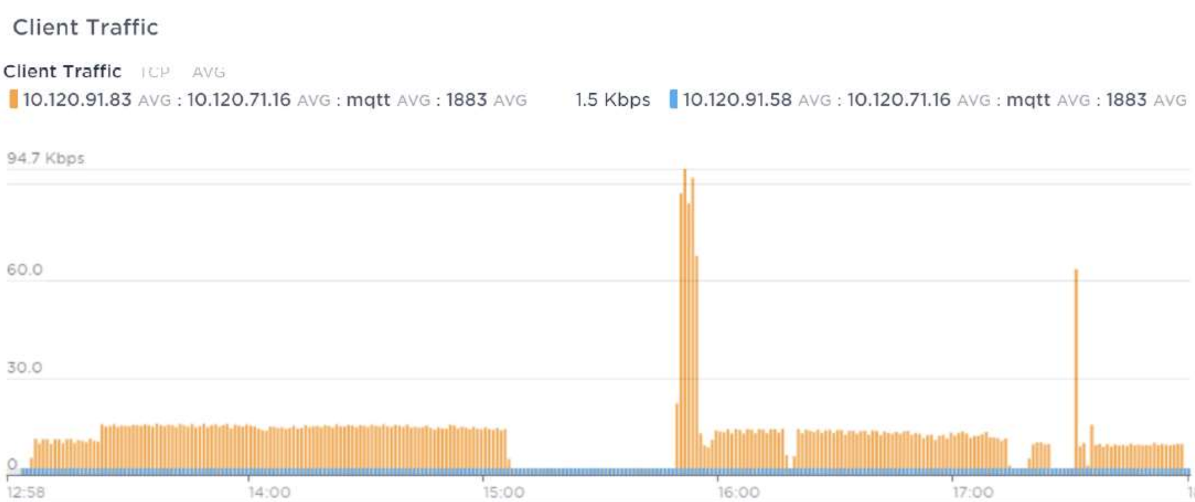

Figure 32 - Volume of traffic (data) *received by* Control Model *from* Sensor Array (orange bars) and Feedback system (blue bars)

[9] https://accedian.com

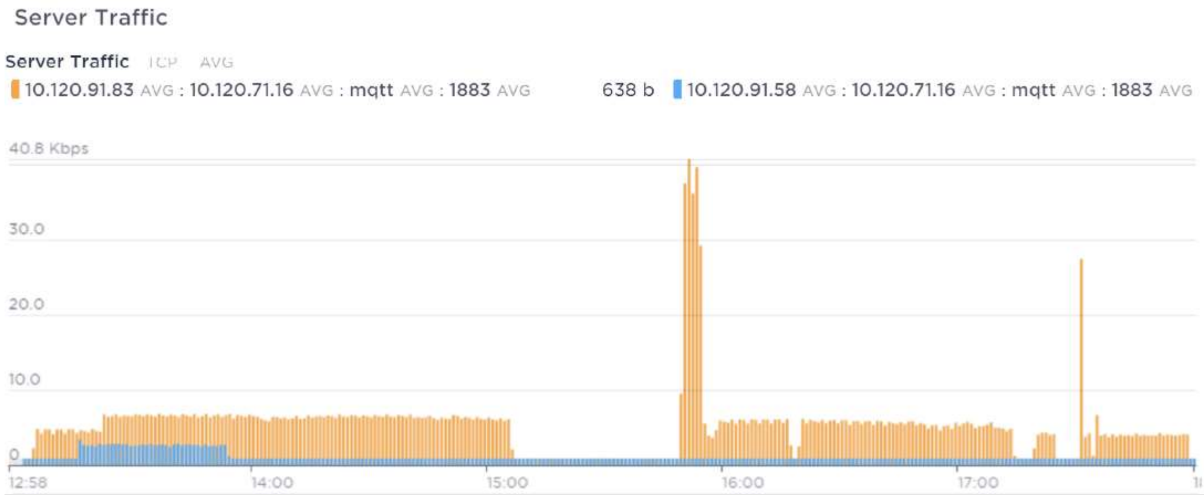

Figure 33 – Volume of traffic (data) sent *from* Control Model *to* Sensor Array (orange bars) and Feedback system (blue bars)

The Feedback System was designed to only be in operation during the injection phase of the manufacture. This phase was between 13:15 and just before 14:00. Therefore the Feedback Systems' (blue) bars in the figures stop after this point.

Figure 31 shows the latency for data transfer between the Sensor Array and Control Model was around 30ms, which aligns with the ping data recorded in Table 6. The latency from the Feedback System to the Control Model appears to be significantly higher (around 75ms); however, this does not match what was seen. It is suspected that the higher latency recorded is a feature of the MQTT message protocols acknowledgment system, as real-world latencies were closer to 30ms.

The volume of traffic between the Sensor Array and Control Model is shown in Figure 32. During normal operation the volume of data appeared to be around 15 Kbps, this low volume was expected. After the major network outage between 15:00 and 16:00 the Sensor Array reconnected and appeared to send a large amount of data.

The traffic volume sent by the Control Model to the Sensor Array and Feedback system is seen in Figure 33. Again, these sub-10 Kbps volumes were expected as the data packages traversing the network were relatively small.

5G Assessment

5G Benefits

Overall, the Closed Loop LRI system worked well over 5G. Prior to the point where connection to the network was lost, the network achieved very low latencies allowing for rapid transfer of data and commands. The Closed Loop Control system (Sensor Array/Feedback System/Control Model) was able to work as designed and was fully executed before connection was lost.

5G does have the potential to work well in a manufacturing environment - the latencies achieved were impressive, and signal coverage was good. The edge computing on the servers also worked well and enabled high system flexibility.

5G Issues and Future Work

The main issue with the 5G network was its reliability. The Data Visualisation System (Sensor Array/Dashboards) worked well while the connection to 5G was live, however major problems occurred when the connection was dropped. The drop out not only caused a total loss of data recording during the outage window but had knock on effects to the quality of the data collected even after the connection was re-established (due to the nature of the sensors).

Reliability is the primary challenge that must be addressed before this kind of system could be used in industry. The drop in connection during the 5G manufacturing trial was not unexpected. It has proved incredibly challenging to develop the ultra-high reliability supposedly achievable with 5G. One of the primary reasons for this is that 5G devices (such as routers) are still immature, especially when used on 5G SA networks. A reliability of 85.6% is poor – network reliability is usually categorised as 99.9% and higher. If a more comprehensive closed loop control system was developed which used 5G as its means of communication, any loss in connection would at best lead to a loss of data or a scrapped part, and at worst could result in serious safety hazards.

Additionally, this project was not able to assess the mMTC capability of 5G. This feature allows thousands of individual devises to connect simultaneously to a 5G network in high density. This kind of setup would be needed where the number of sensors/controllers was increased, for instance in the LRI manufacture of large structures. mMTC therefore requires further testing in a manufacturing environment before it can be verified.

Finally, prior to the implementation of a private 5G network in a manufacturing setting, a comprehensive signal coverage study should be performed. This must include assessing potential areas of signal interference such as large electrical machines or steel framework. It is much easier to plan and implement correct signal coverage than to try to retrospectively fix coverage after the network is installed.

5G Conclusions

5G has the characteristics to meet many of the key challenges involved with implementing closed loop manufacturing systems. Through the industrial real-world testing of a 5G network, this project has found that the low latencies needed by closed loop manufacture can be achieved with 5G (~30ms). Further, the edge compute capability worked well for running control models.

The main challenge identified for using 5G on these kinds of use cases is developing ultra-high reliability. 5G-enabled devices and the SA network technology itself cannot currently provide the level of reliability needed for safe control. That said, as device and 5G private network technology improves, the remaining barriers to using 5G in a closed loop manufacturing setting should be removed. Progress is already being made in this area; more 5G devices are coming to market that should work effectively on SA 5G networks.

Finally, as the use case was unable to test 5G mMTC, it should be subject to a detailed future investigation to understand if it can be realistically achieved in industry.

TOSHIBA 5G NSA

As outlined in Assessment Methodology the purpose of the Toshiba 5G NSA network was to test the viability of using a 5G network – built using COTS hardware and Opensource software – in an industrial setting. The Closed Loop LRI system was used as the test bed for this assessment. This section details the build, test, and results of this investigation.

Introduction

Toshiba have provided a separate 5G Non-Standalone (NSA) network in the NCC. The 5G implementation that Toshiba BRIL (Bristol Research Innovation Laboratory) have been experimenting with is based on the open-source project Open Air Interface (OAI).

OAI is led by the OpenAirInterface Software Alliance (OSA) based in the Eurecom research centre in Sofia, France. The purpose of OAI is to provide an open platform for telecommunication research by providing software to realise a 3GPP compliant open-source approach to LTE (Long Term Evolution), 5G NSA and 5G SA stacks.

How was it Built

The Toshiba network installed in the NCC is of the NSA configuration. A block diagram is found in Figure 34.

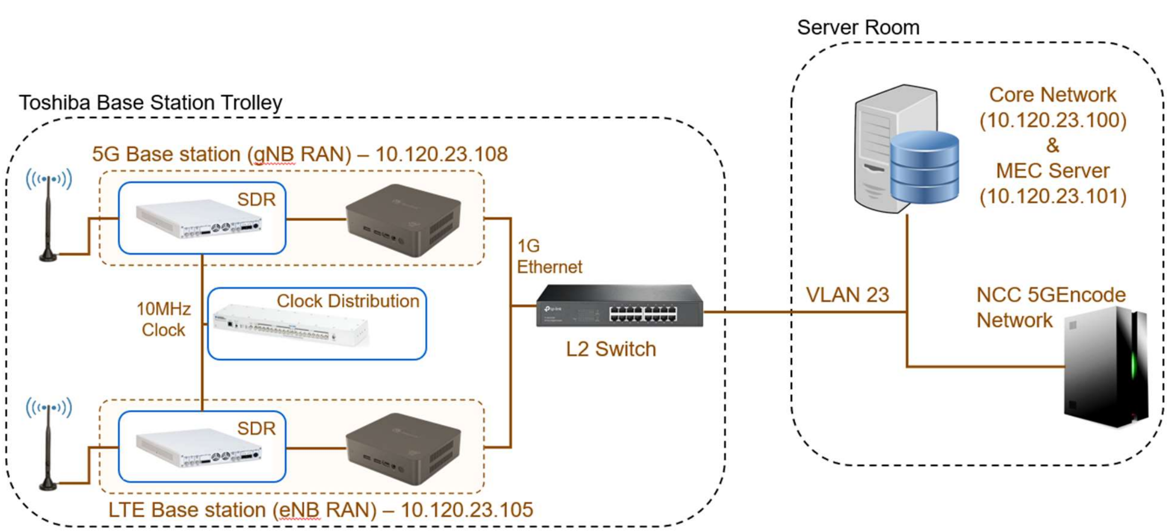

Figure 34 - Diagram of Toshiba's NSA Network

The network is split into 2 parts, Base Station and Server Room.

The Base Station consists of the following:

- eNB RAN (Radio Access Network) – Radio for LTE communication - PC & SDR
- gNB RAN – Radio for 5G NR communication - PC & SDR
- Clock Distribution – Synchronising hardware for the eNB and gNB

The Server Room contains the following.

- Core Network – Database for registration and endpoint of the Protocol Data Unit (PDU) session
- Multi-access Edge Compute (MEC) systems – For running low latency application code

The parts of the network are made up of commercial off the shelf (COTS) components, such as research grade Software Defined Radio's (SDR), clock distribution units and standard server and PC hardware. The hardware used is detailed below:

Software Defined Radio

The SDR is responsible for the RF layer of communication, it communicates with the host PC via either USB 3 or a fast ethernet link. There are multiple SDRs that are compatible with the OAI platform depending on performance needs. We will focus on the National Instruments Ettus USRP series as they have the most support from the OAI project.

For the NCC setup the Ettus USRP B210 was chosen as this has support from the OAI project and is at a fair price point. The B210 has a USB3 interface, and it is capable of up to 40MHz bandwidth using ¾ sampling. Both the eNB and gNB will have 1 USRP B210 each.

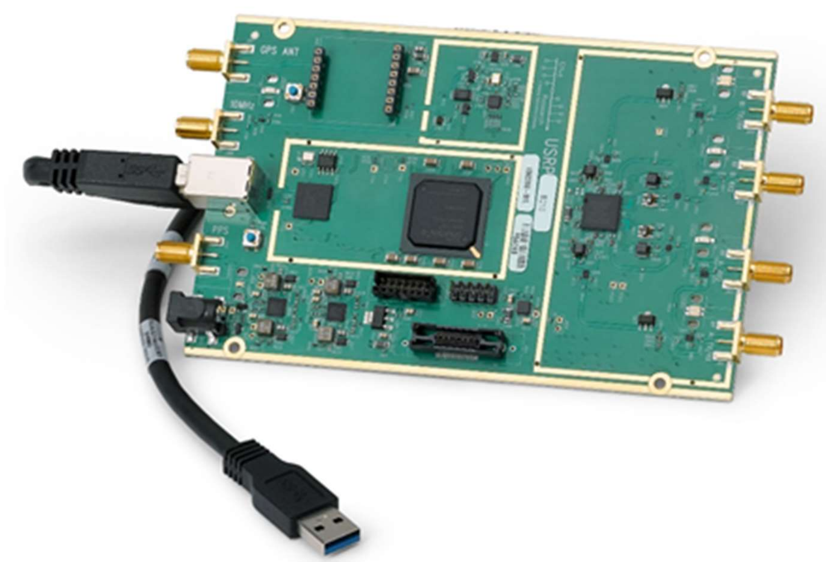

Figure 35 - National Instruments USRP B210

Synchronisation

The eNB and gNB USRP radios are required to be synchronised when used in an NSA network configuration. A recommended way of achieving this for an OAI NSA based system is to use either a GPS Pulse Per Second (PPS) receiver, or a 10MHz accurate clock. A synchronisation product from Ettus is the OctoClock-G. The OctoClock-G can synchronise up to 8 devices using either the GPS PPS or its internal 10MHz clock if a GPS signal is unavailable.

Potentially if the radios are situated far away from each other to make connecting via the OctoClock-G unsuitable, a GPS module can be added to the USRP's which will allow the radios to synchronise via GPS PPS. However, this solution requires an antenna that can receive GPS signals that are traditionally hard to receive indoors.

Figure 36 - National Instruments Octoclock-G

Base Station PC's

For each base-station radio there is a requirement for a high-powered PC to perform the processing on the radio data. Each PC ran the Ubuntu Linux 18.04 operating system and had the OAI-RAN software installed. As the OAI-RAN software is a real time system it is preferred that a low latency kernel is installed, however in later versions of the software a standard Linux kernel is also usable. For better stability, the PC should have CPU frequency scaling turned off to prevent delays caused by CPU power management. The PC used must be of an Intel X86 architecture as the OAI-RAN software uses certain CPU instructions built into the processor.

eNB PC

The eNB in the Toshiba NSA base station is powered by a custom made mini-ITX form factor PC. The PC is running an Intel Core i7-8700 with 16GB RAM and a 256GB NVMe SSD. The eNB software is less resource intensive and this hardware ran it easily.

gNB PC

The software that runs on the gNB is much more resource intensive than the eNB software. As the software is also still in development it is advantageous to have additional computing power for when advanced features such as MIMO are implemented in the future.

The suggested PC configuration from OAI for the gNB is at least an 8 core Intel i7 processor and 16GB RAM, but preferably a modern Intel i9 with 32GB RAM. The PC that was chosen to meet the specs is the Intel Core i9 Ghost Canyon Extreme NUC Mini - BXNUC9i9QNX3. The i9 Ghost Canyon is a top spec NUC featuring an Intel i9-9980HK processor, it has been fitted with a 256GB NVMe SSD and 32GB RAM.

The PC was chosen for its high performance in a small form factor. Keeping the PC cool is an issue due to the intensive processing required by the OAI-gNB software. The NUC has a custom designed cooling solution from Intel which will keep the PC at optimal levels of performance.

Figure 37 - Intel Core i9 Ghost Canyon Extreme NUC Mini - BXNUC9i9QNX3

Core Network & MEC Server

The Core Network of the Toshiba 5G NSA network is based off the OAI Core Network project. This provides the necessary components such as Home Subscriber Server (HSS) Database, Mobile Management Entity (MME) and the Serving & PDN Gateway (SPGW). These components allow User Equipment (UE) to register with the network and transfer data to the wider network on the NCC.

A Dell Power Edge R640 server was used as the host for several Virtual Machines (VM's) which ran the Core Network and MEC applications. The server has the capability of running numerous edge applications at the same time. The advantage of having MEC applications and the Core Network on the same server is that it lowers latency and data can be accessed easily through the same network interfaces.

Another application from OAI called FlexRAN has been installed on the server. FlexRAN can be used to adjust certain parts of the system, read status of base stations, and do network slicing. Unfortunately, FlexRAN only works on LTE and has not been updated yet for the 5G network.

Software

As mentioned in the previous sections the software running on the network is based on the OAI project. Table 7 details the software versions used including git tags and repository information.

Table 7 - OAI Software Used

Network Component	Software Used	Git Version Tag	Link to Repository
Core Network	OAI-HSS	v1.1.1	https://github.com/OPENAIRINTERFACE/openair-epc-fed/tree/2021.w06
	OAI-MME	2020.w47	
	OAI-SPGW-C	v1.1.0	
	OAI-SPGW-U	v1.1.0	
eNB RAN	OAI-LTE RAN	2021.w10	https://gitlab.eurecom.fr/oai/openairinterface5g/-/blob/2021.w10/doc/TESTING_GNB_W_COTS_UE.md
gNB RAN	OAI-NR RAN	2021.w10	

Some of the core network components have been depreciated such as the MME, so it is advantageous to investigate upgrading the core to some of the latest versions.

There is also an OAI project that implements an SA system which will negate the need for an eNB base station and the clock distribution unit. However, the software is not as mature as the NSA and therefore has not been used for the Toshiba system.

User Equipment (UE)

To connect with the network a capable UE is needed. For the 5G Encode network Toshiba has purchased a Quectel RM500Q-GL USB dongle. The USB dongle shows up as a QMI device on Linux machines and can be used as a network interface.

Each UE needs a SIM that is registered with the network. For the Quectel dongle it was discovered that only certain Public Land Mobile Network (PLMN) registrations would allow the dongle to access the 5G network, even if LTE were working correctly.

For Toshiba's network in the NCC the PLMN of 001 01 was chosen as this is accepted by manufacturers as a test network setting. PLMN ID's for private networks are still under standardisation within 3GPP and associated bodies.

Frequency Bands

The Toshiba NSA network requires 2 licences from Ofcom to legally broadcast in the NCC. Toshiba has acquired 2 licences from Ofcom, 1 for Band 40 LTE (10MHz at Centre Frequency (Fc) 2395MHz), the second for Band N77 5G (80MHz at Fc 4155MHz). With testing it has been discovered that although it is possible to connect the Quectel device in LTE only Band 40, it does not work as an anchor band for the NSA configuration.
For our test for the LRI interface the NCC have allowed Toshiba's network to broadcast on their LTE Band 3 licence as this configuration works with
the Quectel dongle. The broadcast frequencies used are in Table 8.

Table 8 - RF Frequencies Used During LRI Use-Case

Radio	Frequency Band	Centre Frequency (Fc) Broadcast	Bandwidth
eNB (LTE)	Band 3 (FDD)	1845MHz Downlink 1750MHz Uplink	5MHz
gNB (5G)	Band N77 (TDD)	4155MHz UL/DL	40MHz

Other Network Capabilities

Toshiba's 5G network can support network slicing, in the form of radio resource slicing, as discussed in Appendix B – Radio Resource Slicing.

Integration with LRI Use-Case

The integration of the Toshiba NSA network and the LRI use-case was achieved as shown in Figure 38 below.

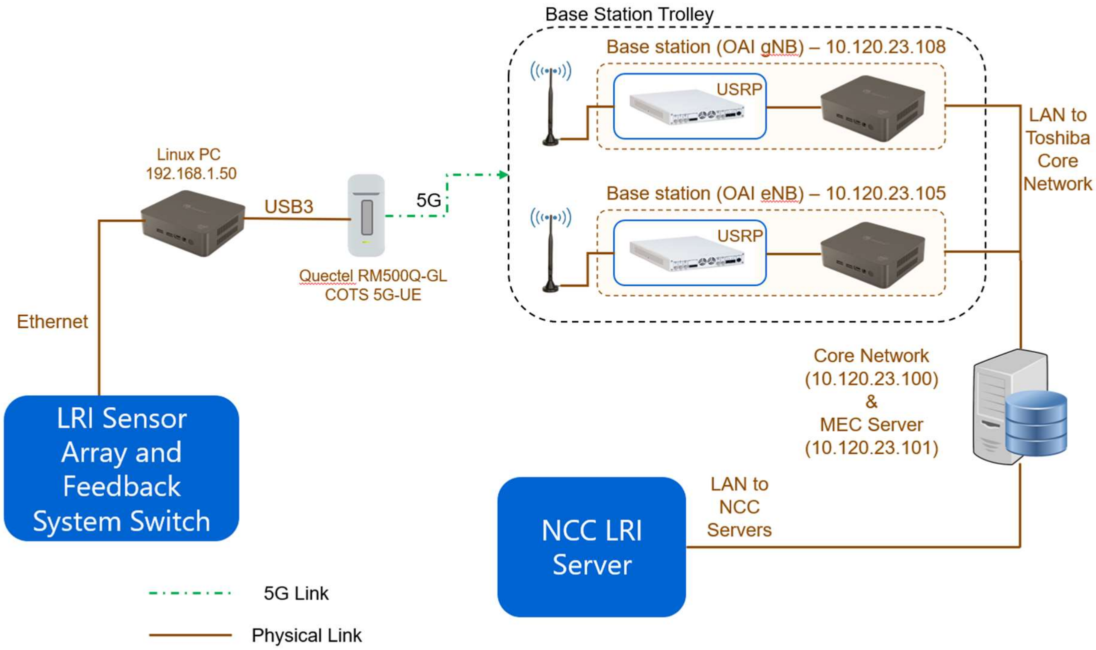

Figure 38 - Diagram of Integration Between Toshiba's NSA Network and the LRI Use-Case

The Linux PC on 192.168.1.50 acts as a bridge between the LRI and Toshiba 5G networks. The devices in the LRI network that need to send data to the LRI servers set their gateway to route via the Toshiba Linux PC. The Toshiba Core Network can directly see the LRI use-case servers, as such the packets are able to be routed out of the network to the LRI servers without issue.

5G NSA Network Performance

The Toshiba network was utilised during a test infusion of the LRI system as described in the Use Case Testing section.

The LRI use-case is the first test of the Toshiba NSA network in an industrial setting. All the testing prior to the installation at the NCC has been done in lab conditions. Some of the main differences between the factory and lab conditions are that there are many more sources of RF interference (including other cellular networks and industrial communication protocols from manufacturing equipment), more personal devices from workers and lots of RF blocking material in the area such as metal machinery and ducting.

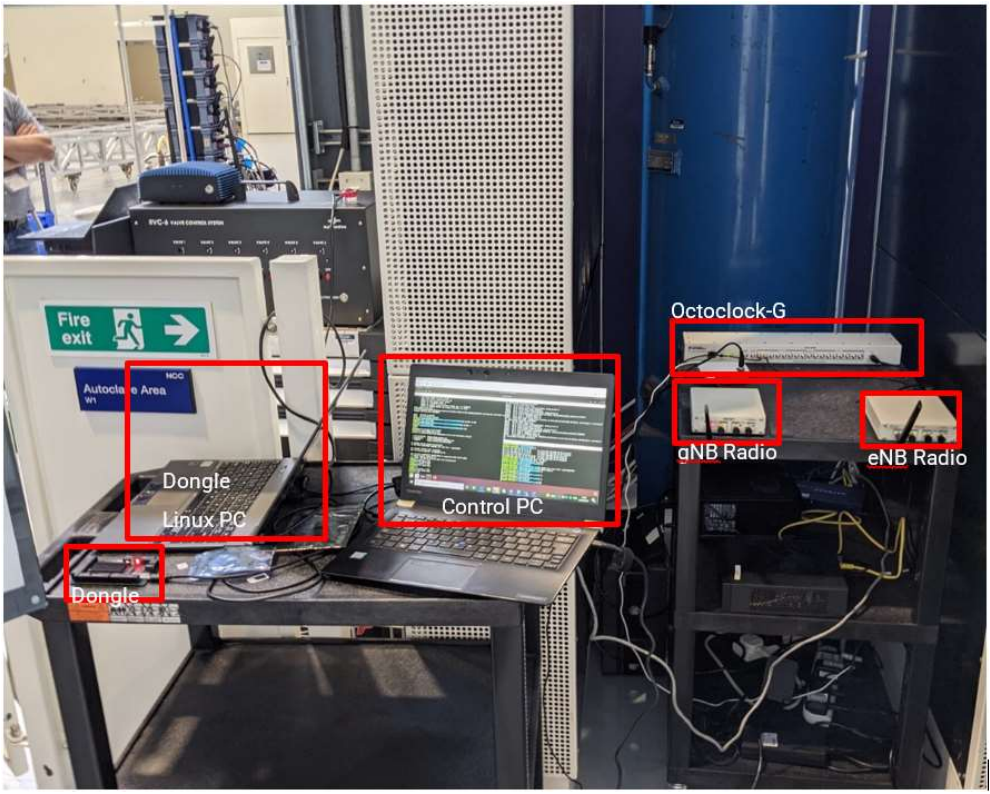

Figure 39 - Picture of LRI Use-Case Setup

Test Performance

The LRI test with Toshiba's NSA 5G network went well. The closed loop control of the infusion valves was successfully run over the Toshiba 5G network.

Unfortunately, after about 1 hour 20 minutes the 5G base station crashed. As the network is an NSA system, the device was switched over to the Toshiba LTE network where it was still able to transmit data, albeit with lesser downlink and latency performance than 5G. After 10 minutes on the LTE system the connection to the Quectel dongle was dropped by the network.

It is suspected that the reason for both the 5G base station crashing and LTE dropping the device is that some unexpected devices attempted to roam on the network. Although the other devices did not gain access to the network, it did manage to disrupt the scheduling of the connected device leading to it being dropped by the base station. The LRI test was swapped to run on the NCC 4G network for the overnight cure and minimal amounts of data was lost.

Whilst the test was running, several data metrics were logged on the network as detailed below.

Latency

A ping test was performed during the test with a period of 1 ping every second. Figure 40 shows the results of the overall test.

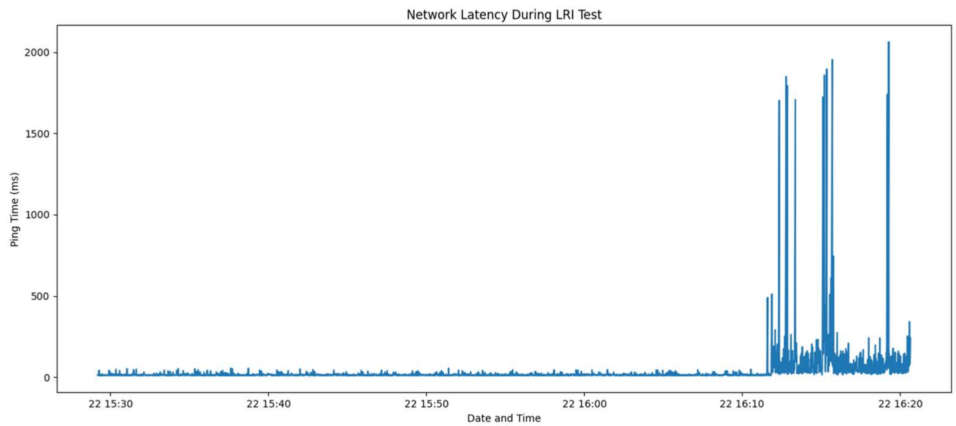

Figure 40 - Graph of Latency During LRI Test

The erratic behaviour towards the end of the test at about 16:12 was when the 5G base station and resulting switchover to LTE occurred. Table 9, Figure 41, and Figure 42 below shows results of the ping test before and after the 5G crash.

Table 9 - Table of Latency During LRI Test

Metrics	Data Before 16:10	Data After 16:10
Avg Ping	14.1ms	129.1ms
Max Ping	54.9ms	2064.0ms
Min Ping	8.6ms	9.6ms
Standard Deviation	6.0ms	268.7ms

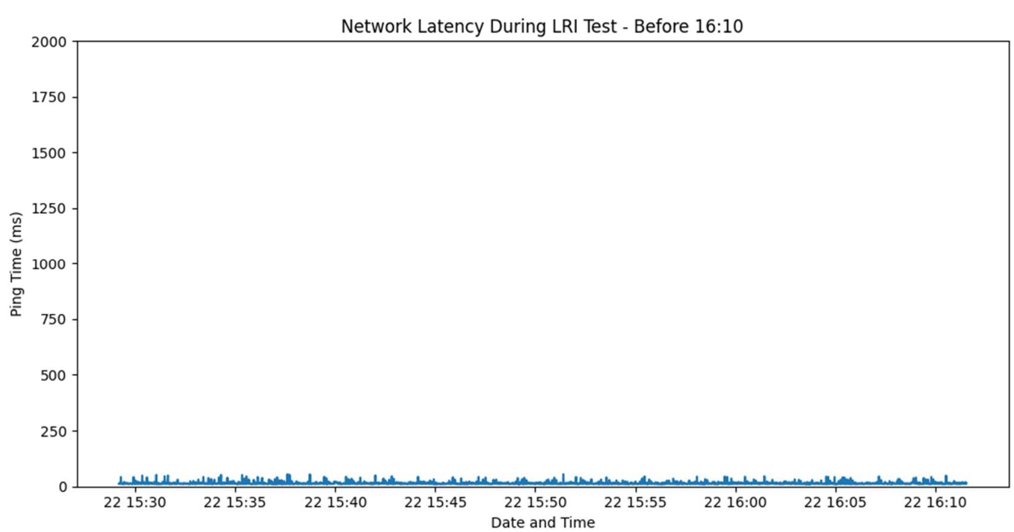

Figure 41 - Latency During LRI Test Before 5G Crash

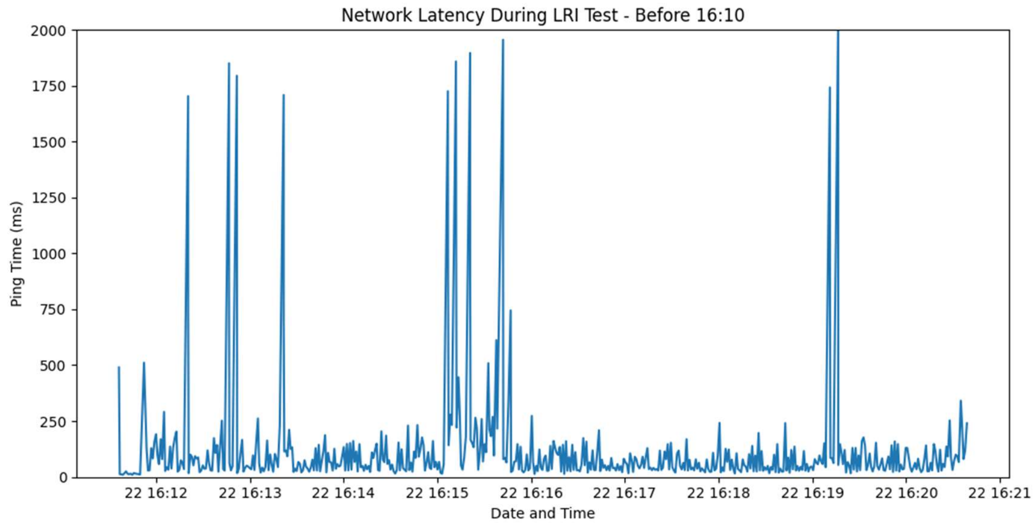

Figure 42 - Latency During LRI Test After 5G Crash

It has not been determined if the spikes in latency are related to the air interface interference or if there is a processing delay on the PC side of the network.

Network Speed

The bandwidth performance of the network has been measured in the Toshiba BRIL lab using an iperf3 test between the Linux machine with the Quectel 5G dongle and the Core Network endpoint. Performance is shown in Table 10 below.

Table 10 - Lab Iperf3 Performance

Mean Downlink	22 Mbps
Mean Uplink	0.8 Mbps

The low uplink performance comes from the slot configuration of the OAI system on the gNB. Unfortunately, the software version that was used on the test did not allow for easy configuration of the DL/UL slots and became unstable when not in the default configuration of 7DL/2UL slots.

Transferred Data, Stability & Packet Loss

Figure 43 shows the total data transferred during the LRI test on the 5G network.

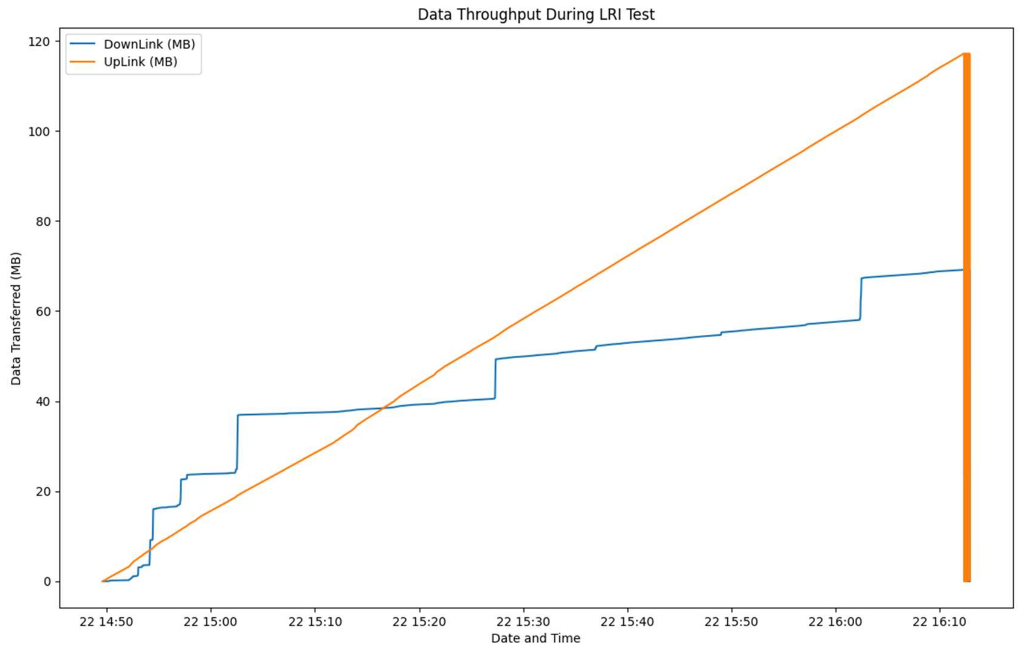

Figure 43 - Graph of Data Transferred During LRI Test

The erratic behaviour towards the end of the graph is when the gNB crashed. The uplink is a steady linear increase due to a constant amount of data being sent from the LRI equipment to the server over the network. The downlink shows more of a step function at various times. These would correspond with the closed loop control sent from the server to the system.

With regards to the RF signal the network performed robustly in the industrial environment with minimal radio interference from unknown radio sources. Although range was limited, this could be improved with amplification of the radio signal. As mentioned above in Test Performance there is a need for further software development to address the stability of the network. This should be focused on the roaming issue, as it cannot be assumed that other devices in the area will not attempt connection.

With regards to the environmental concerns, there did not seem to be any discernible difference between the NCC and BRIL's lab setup with latency and bandwidth, nor did there seem to be any packet data loss during the LRI closed loop test.

Conclusions & Lessons Learned

Looking at the specific use-case testing in the NCC environment it was interesting to see the differences between a lab environment and a busy factory. Issues that were expected such as range and RF interference did not seem to be a problem for the network. However, legitimate device interference from employees' personal devices attempting to connect and roam to the network did cause some significant problems with stability.

The roaming issue had been overlooked previously as the majority of Toshiba BRIL's OAI testing has been performed in controlled conditions with single devices. Adding unpredictable actors into the system had a negative effect on parts of the system that are not production ready yet. It is suspected that the main cause of the issue was the version of the OAI gNB software that was used. The software is less mature than its LTE counterpart and is still in active development. Updating the gNB software to a later version will be investigated for future tests.

The Toshiba NSA network was currently not very well ruggedised for industrial environments. For one-off testing this can be controlled by limiting exposure to chemicals, dust, and other electrically damaging debris. However, a suitable enclosure should be sourced if the base station were to be more permanently installed in a harsh environment.

There are definite limitations of basing the network from an open-source software project. OSA have provided numerous tutorials and guides on the system, however they still require a working understanding and knowledge of low level 5G/LTE systems, as well as experience with Linux and networking that may not be applicable to everyone. The lack of warranty and the technical barrier to entry of getting the system up and running can prove daunting if inexperienced.

With the issues stated above it is clear that there are several improvements necessary before the network can be taken into a full deployment in an industrial environment. However, the technical achievement that the OSA have reached should not be understated. With more years of maturity and development OAI is an incredibly promising project that will have reaches far outside the research community that is developing it. Toshiba has found benefits from the open and programmable nature of the OAI network. It has allowed for the same hardware to be used for different licence bands, and as the code is open source there is opportunity to build upon the codebase with new technology for research.

As a parallel exercise Toshiba BRIL is also investigating a vendor provided 5G SA network solution based on the O-RAN architecture to understand how the new open architecture complements the 3GPP specification. Though the OAI open-source solution is far cheaper than a vendor provided system, stability issues and the barrier to entry currently present in the software make it hard to recommend OAI as more than a research tool.

APPENDICES

Appendix A – Systems Engineering and Requirements Development Process

The Systems Engineering and Requirements Capture Process

As outlined in the introduction, the LRI process is complex, highly manual, and dependent on the skill of the manufacturing operator. Numerous variables such as resin temperatures, infusion pressures, fabric permeability, resin viscosity and many others effect the quality of the final composite component. Because of its complexity very little has been done to practically automate it and bring greater intelligence to the process.

A Systems Engineering (SE) approach was used in the design and development of the Closed Loop LRI system. To start with the scope of the system was left open to capture the full requirements for a closed loop LRI process. During this phase cost, time to implement, and available resources were not considered; this was done later when choosing which requirements to implement. The stages of the SE approach are shown in Figure 44.

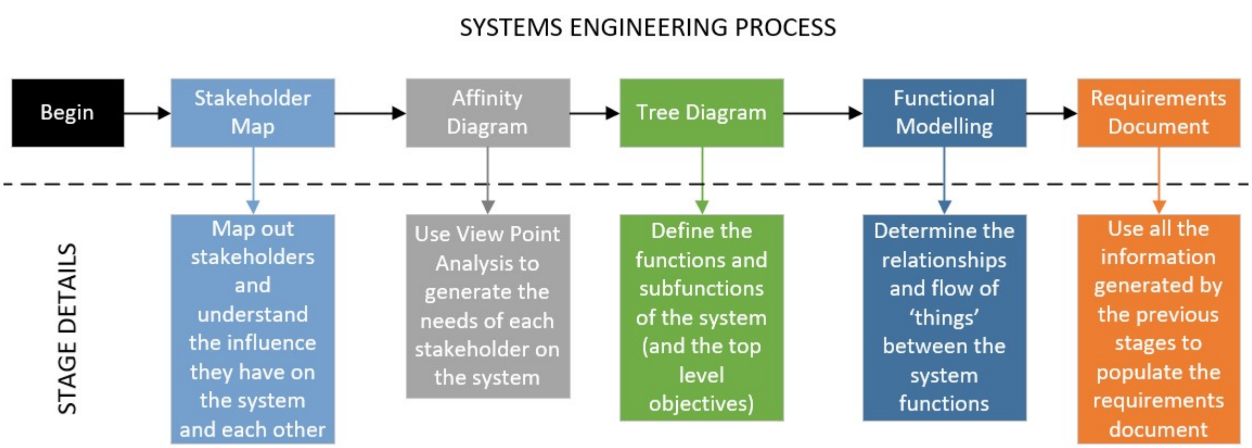

Figure 44 - The Systems Engineering process

The SE approach used in this project was done pragmatically based off the available time, meaning some stages of the more formal SE process were not performed. The details of each stage are as follows:

- **Stakeholder Analysis** – this is used to determine the different groups or 'things' that have an influence or interest in the system. Once stakeholders are generated they are collected into groups of similar interests (e.g. system designers, system users, suppliers). The influence that these stakeholder groups have on the system and each other are then mapped out in a Stakeholder Influence Map.

- **Affinity Diagram** – A tool called Viewpoint Analysis is used to systematically determine the needs each stakeholder has on the system (using the Stakeholder Map). This ensures a holistic approach to generating the system requirements without an overfocus on one or two stakeholders. These needs are then collected into groups that are similar - or share 'affinity' – in a diagram, and this outlines the key functionality of the system.

- **Tree Diagram** – The requirements from the affinity diagram are taken and organised in a tree structure outlining top level functionality and sub-functionally at different levels. The diagrams top level functions are used to determine what sub-systems will need to be developed. **NOTE – requirements must be written as functions, not solutions.**

- **Functional Modelling** – The Tree Diagram is useful for determining whole system and sub-system functionality; however it gives a siloed view. Therefore, there is a need to understand how each sub-system will interact with each other - Functional Modelling is used to determine this. A diagram is made mapping out the inputs and outputs every sub-system has on each other, and this is used to generate additional requirements based off their interactions.

- **Requirements Document** – The functionality outlined in the Tree and Functional Modelling diagrams are transferred into a formal requirements document.

It's important to note that during this process no solutions are proposed yet. The requirements document consists only of system functions, in other words "what the system has to do to meet the top-level requirement – closed loop LRI".

Requirement Selection

As previously stated, the requirements capture process was left open to understand the functionally needed for a full Closed Loop LRI system. Once the requirement set was developed, the scope of the Closed Loop LRI system was narrowed by choosing specific requirements to implement. This was done by selecting the system requirements that met the overall requirements of the programme (5G ENCODE), and that would be deliverable within the bounds of the project (budget, time, resource). Additionally, a technology assessment was performed to understand what sensors, controllers, and software could be realistically procured/developed within the project.

It was not within the scope of this programme to implement a compressive closed loop system to monitor and automate every element of the LRI manufacturing technique. The aim of this programme was to take the first steps towards a fully closed loop LRI process by **targeting specific elements of the technique to monitor and automate**. In addition to the benefits this initial automation would bring, the architectures, underlying systems, and knowledge base that would enable a fully closed loop system to be built in the future were also developed.

Appendix B – Radio Resource Slicing

Toshiba's 5G network is fully capable of radio resource slicing functionality. Slicing of radio resources is crucial for providing strict performance guarantees in private/local deployments, particularly under multi-service co-existence scenarios.

The slicing functionality is achieved through a programmable software-defined RAN platform which provides necessary APIs for defining slice requirements and controlling radio resources at the base station. Slicing takes place at application level, i.e., each application (and associated users) is allocated a radio slice which has been customized to its requirements. Dynamic relocation of users from one slice to another is also supported.

Toshiba has recently demonstrated the concept of a private 4G/5G network with radio resource slicing. The demonstration considers three distinct applications: closed-loop control, event-triggered control, and video streaming, and shows the importance of slicing for providing performance guarantees. Further details about demonstration and radio resource slicing strategy are available in the following reference.

Jaya Thota and Adnan Aijaz. 2020. Slicing-enabled private 4G/5G network for industrial wireless applications. In Proceedings of the 26th Annual International Conference on Mobile Computing and Networking (MobiCom '20). Association for Computing Machinery, New York, NY, USA, Article 75, 1–3.
DOI: https://doi.org/10.1145/3372224.3417325
Public copy: https://arxiv.org/pdf/2008.04866.pdf