Final Report

WP3.3.2: Automated Preforming Technology

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1	Initial issue

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's biggest investments in using 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 is designed to validate the idea 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 the UK industry exploits the 5G technology and remains a global leader in the development of robust digital engineering capabilities when implementing complex composites 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 (URLL/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 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 details an industrial use case relating to in-process verification of composite materials using a vision-based system. The main barrier to these types of verification systems being more widely accepted across industry is the significant infrastructure requirements for them to operate effectively. These requirements are driven from the need to process the massive amounts of data generated and the need for low latency feedback, which leads to them needing to be installed in fixed locations with large set up, and integration costs.

This use case aims to demonstrate how a decrease in infrastructure requirements and increased in flexibility offered by exploiting 5G capabilities, can make this technology more accessible for industry.

5G has ultra-fast, high bandwidth, low latency capability enabling large amounts of data to be sent and received wirelessly in near real time. The Gigabit uplink and downlink speeds present an opportunity for this use case as vast amounts of data are generated during each scan. The high throughput ability of 5G combined with the ultra-low latency theoretically lend themselves perfectly to this application as large volumes of data can be communicated in near real time.

To assess feasibility and understand solution architecture prior to 5G network availability, a baseline test was conducted using 4G LTE on a similar vision system. This test proved that vision systems of this nature can communicate data using cellular technology, however low 4G communication speeds led to the scan time being significantly increased while the quality of the gathered data was reduced.

Upgrading the industrial vision system at the NCC to 5G was successful and allowed data to be communicated to a virtual server in near real time, achieving latency values in the region of 14ms. The uplink throughput was still not sufficient to run a scan at the same parameters as the original wired set up but vastly improved compared to 4G. A maximum uplink throughput achieved using 5G was 18Mbps (2.25MBps), far from the 900Mbps seen when using CAT7 cable. The lack of comparative communication speed led to data fragmentation and network instabilities when attempting to pass large volumes of data across the network, often leading to a cease in data flow. The root cause of this has not been fully identified, however, a reduction in uplink data volume, through reduction of MTU size and scan speed, vastly improved the stability of the connection and the quality of the output.

The 5G connection did allow the processing PC to be removed from the system, significantly reducing the weight and footprint of the end effector from 45kg to 3.5kg. This allowed the use of a smaller collaborative robot to accurately position the system reducing robot system cost (~88% reduction) and, in turn vastly reducing the integration cost required to set up when compared to the original deployment (~98% reduction).

The use of industrial 5G for an application such as this is possible but there are trade-offs that must be considered. There is a significant reduction in both robot system cost and integration cost, leading to a much more flexible and easily deployable system. However, until an increase in 5G uplink throughput is possible, the time to scan will be greatly increased to achieve the same quality of output.

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ABBREVIATIONS

APC	Automated Preforming Cell
FOD	Foreign Object Debris
NCC	National Composites Centre
CPE	Customer Premises Equipment
GV	GigE Vision
GVCP	GigE Vision Control Protocol
SME	Small to Medium Enterprise
MTU	Maximum Transfer Unit
RAN	Radio Access Network
IP	Internet Protocol
MAC	Media Access Control

1 INTRODUCTION

1.1 Industrial Challenge

Automation technologies are becoming increasingly more available and affordable, and as this technology is adopted more widely across a range of industries, more and more opportunities for innovation present themselves.

Composite production has always been synonymous with a high level of quality control as the quality of a component directly impacts its performance. One method of achieving high quality control is using in-process verification sensors at each stage of the manufacturing cycle, to give accurate and useful data about the material. As a direct benefit, the addition of an automated defect detection system allows the user to immediately identify when and where any discrepancies in the material or process occur, in turn reducing the need for re-work and scrapped components. Indirectly, these systems also allow the increased adoption of dry fibre into high value manufacturing to become a more feasible option, driving operation costs and energy utilisation down as the need for an autoclave is removed.

These systems however, come with a series of limitations; they can be expensive to install and integrate with existing technologies, there is a significant infrastructure requirement for them to operate at full capacity and often can be inflexible and difficult to redeploy. These limitations can often lead to this technology not being as widely adopted into industry and even less so in SME's. Consequently, composite component can go through an entire manufacturing cycle before receiving an NDT inspection, at which point, should there be any discrepancies the component must either be scrapped or sent for expensive re-work.

Within the NCC there is a cell called the Automated Preforming Cell (APC), shown in Figure 1, used for researching and streamlining automated preforming processes and technologies. Within the cell there are two Kuka robots that are used to position various NCC built and bespoke end effectors used for preforming, inspection and cutting of composite dry fibre.

Figure 1 Automated Preforming Cell at NCC showing both Kuka Robots

One such end effector is the "Verification Rig" as it's commonly known (Figure 2). This is a bespoke system that combines two of Profactor's inspection sensors, namely the F-Scan vision system and the L-Scan laser line scanner. The current deployment of this technology within the NCC requires significant infrastructure to operate and makes use of the larger Kuka KR 500 robot (shown in white in Figure 1), as the end effector assembly weighs ~45Kg.

Figure 2 Profactor F-Scan & L-Scan Verification Rig

The assembly is so large as there is a processing PC hosting the Profactor application contained within the end effector assembly, as the vast amounts of data produced must be captured, communicated, and processed in near real time. Furthermore, the APC is a highly flexible cell and mounting the PC elsewhere would mean sacrificing the ability to have complete modularity, while adding latency into the system. The ultra-high-resolution data generated during this application coupled with large robots to position the sensor, mean that the level of infrastructure required for this task is significant. This combined with a classically wired set up, used to achieve the required ultra-fast communication speeds, lead to these systems being not only expensive to set up and run, but also inflexible, complex to configure and difficult to quickly redeploy.

1.2 Project Objectives

1.2.1 Overarching Objective of Use Case

This use case aims to investigate and demonstrate how automated defect detection systems can be made more commercially accessible using innovative digital technologies and 5G.

The objectives of this use case can be summarised by three main points:

1. **Demonstrate a reduction in infrastructure costs** when compared with an existing deployment.
2. **Demonstrate an increase in capability** when compared with an existing deployment.
3. **Demonstrate an increase in flexibility/ability to deploy** when compared with an existing deployment.

1.2.2 5G in Relation to This Use Case (5G Opportunity)

5G as a technology can communicate massive amounts of data in near real time, all without the need for expensive and extensive hardwired data connections. Vision based systems used for automated defect detection require high speed, low latency, ultra-reliable communication between the sensor and the processor. The reason being that these sensors are most commonly used in conjunction with a robot/gantry to position the sensor. The positional data is communicated every 10-12ms, meaning high speed connection is critical in synchronising the sensor images with the positional data.

This use case will test the uplink throughput and low latency capability of 5G, as large volumes of data are generated at the sensor and must be communicated in near real time to the processing location. Substituting the wired connection with ultra-reliable, high-speed 5G removes the need for a bulky processing PC at the sensor location while maintaining flexibility, thus significantly reducing the footprint of the system. A smaller system can be used with a smaller robot, thus reducing the required infrastructure for this application, driving costs down and making this technology more accessible to industry.

1.3 Overview of Use Case

This use case will focus on the Profactor “Verification Rig” assembly within the NCC to investigate how this technology can be made more flexible and easily deployable. The F-Scan sensor will be removed from the assembly, upgraded to 5G and compared with the previous deployment of this technology using a wired connection, to assess its performance.

1.3.1 Top Level Architecture

The architecture of a system like this can be broken down into a number of fundamental elements, namely a sensor, a positioner, a means of transferring the data and a means of processing the data as shown in Figure 3.

Figure 3 Top Level Architecture

The sensor is used to generate valuable fibre orientation data about the surface that is being scanned, in this case a dry fibre composite preform will be investigated as this has the most relevance to industry. The sensor is held in place by a robot arm which is critical for both achieving high quality scans and getting accurate positional data of exactly where the sensor is in space. The data generated by the sensor, combined with the joint angles of the robot, must be sent via some means (most commonly CAT7 data cable), to whatever machine is hosting the software used to process it.

Breaking the system down into its fundamental elements allows for innovation within each. There is potential for sensor and positioner to be reduced in size and weight, the data transfer can be made wireless, and the processor can be made virtual. All of which combine to give a much more flexible and potentially cheaper system.

1.3.2 Use Case Metrics

To assess the level of success within this project, several use case specific metrics will be gathered. These use case metrics relate to the physical system and the benefits seen from a reduction in footprint, namely a reduction in integration cost and increase in flexibility.

1.3.2.1 Machine Integration Costs: Reduced Infrastructure Costs

How it is measured: Original integration costs versus new integration costs.

Unit: £

Detail: The use of 5G can remove the need for long extensive hardwired data lines that are costly and time consuming to install. A smaller robot will very likely attract less integration and installation cost than a larger robot. Combine this with the smaller robot housing a built-in safety circuit and the overall system costs will be significantly less than the original deployment.

1.3.2.2 Machine Integration Costs: Robot System Costs

How it is Measured: Original Robot Costs versus New Robot Costs

Unit: £££

Detail: The use of edge compute can remove the need for a high-powered processing PC on or beside the end effector. Centralising this compute power in the comms room means that the end effector can be significantly smaller and thus a much smaller robot can be used with the system. A smaller robot will very likely cost significantly less than a larger high payload robot, and standard comms room hardware used for processing will make the industrial deployment cheaper.

1.3.2.3 Increase in Flexibility: Increased Access to Tight Spaces (Capability Increase)

How it is Measured: Spatial Analysis/Reduction in End Effector Size

Unit: Measurement

Detail: By removing the processing PC from the end effector the sensor is significantly smaller and less bulky. This allows the sensor to be manipulated much more easily and the likelihood of a crash when inspecting a tight radius is significantly reduced, meaning an increased ability to scan more complex geometry at reduced cost and risk.

1.3.2.4 Increase in Flexibility: More Readily Deployable

How it is Measured: Redeployment Demonstration and Use Case Costs

Unit: £££

Detail: Using 5G and edge compute will allow the end effector to be significantly smaller and lighter, meaning a smaller robot with built in safety can be used to manipulate and position it. The overall deployment cost of the new system including all elements of the use case (excluding sensor cost as this is common across both) will be significantly less than the original.

1.3.3 Network Metrics

In order to assess the level of suitability of 5G for this application, a number of network specific metrics will be gathered during testing. Unlike the use case metrics, these relate specifically to the 5G performance and how it enables the data transfer.

1.3.3.1 Latency

How it is Measured: Pings

Unit: Milliseconds

Detail: Latency is a measure of how quickly packets are sent across the network. A common latency value for near real time applications such as this is <10ms, as is consistently seen when testing on a wired connection. 5G is theoretically capable of <10ms latency and will therefore be investigated to observe how well the data is synchronised with the robot position.

1.3.3.2 Uplink Throughput

How it is Measured: Radio Metrics

Unit: Kbps

Detail: Throughput is a measure of the rate at which data flows across the network. An application such as this will require a significant uplink throughput as large volumes of data are generated at the sensor location and transferred across the 5G to the processing location.

1.4 Development Journey

This use case was developed as a result of discussions with members of staff within the NCC as well as conversations with representatives from industry. One common takeaway was that there is a lack of in-process defect detection in use both within the NCC and further afield. Being able to deploy a verification system on a shop floor in collaboration with the individuals producing components would mean not only in-process verification but the ability to rapidly correct any defects before the manufacturing process continues.

As mentioned previously the blockers to this technology being more widely adopted include large and expensive robots often dedicated to performing one specific task, leading to inflexibility and making redeployment elsewhere in the workshop difficult. The Profactor verification rig was selected for this use case as it is industrially relevant and a prime example of where a reduction in infrastructure requirement could unlock capability.

By removing the F-Scan sensor from the assembly the overall weight is reduced from 45kg to just 3.5kg, therefore it was immediately clear that collaborative robots could be used, allowing for the system to be deployed alongside humans without the need for guarding. With ease of deployment, collaborative functionality, and increased flexibility in mind; Profactor, along with internal staff from the NCC including automation and metrology engineers, were engaged to develop a set of requirements that this demonstrator must satisfy. Requirements were broken down into functional and non-functional and are outlined in Sections 1.4.1 & 1.4.2.

1.4.1 Functional Requirements

Functional requirements relate to the physical 5G enabled verification system and the function it must perform. Ideally the system would perform exactly as it did before the 5G enablement, therefore the functional requirements are relatively straightforward.

- The system must use the same interface.
- The system must exhibit identical characteristics as the original system.
- The system must interface with a robot to get positional readout.
- The system must be capable of collecting the same information as the original deployment.
- The system must use the existing application for analysis of data.
- The system must exhibit the same level of robustness as the original system.

1.4.2 Non-Functional Requirements

Non-functional requirements relate to the operation of the 5G enabled verification system and how it performs its task. The system must be able to use the 5G network in the same manner as the wired network, therefore these requirements set out how the network must behave to achieve that.

- The 5G Network must allow the sensor to be able to move freely within the APC cell.
- The 5G network should allow the sensor to be able to move freely between cells in the NCC.

- The 5G network must have an upload latency such that frames are not lost from the camera buffer.
- The 5G network must have a download latency low enough so that sensor control signals are not lost.
- The network density must be such that the sensor can be positioned anywhere in the cell.
- The 5G network must be able to support a Gigabit connection so that the sensor can operate normally.
- The 5G network must be such that it can support jumbo frames (MTU size 9016K).

2 USE CASE INVESTIGATION

2.1 Use Case Architecture (System design)

A detailed network design was conducted in order to satisfy the requirements set out in Section 1.4. One network challenge that was quickly identified was the presence of the GigE Vision (GV) industrial protocol, outlined in Section 2.1.1.

2.1.1 GigE Vision Industrial Protocol

GigE Vision (GV) is an industry standard communication protocol for vision applications typically used in instances where high data rates are required. While the name GigE refers specifically to Gigabit Ethernet connection, GV can be used with any speed ethernet connection. Figure 4 shows a basic outline of how the protocol works.

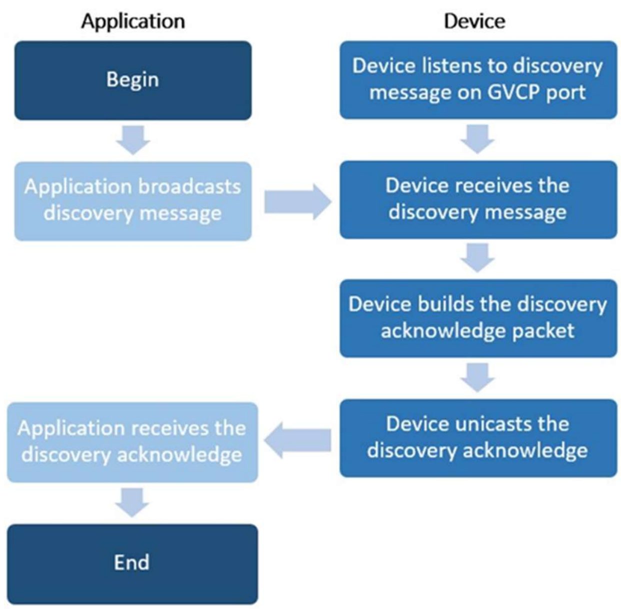


Figure 4 GigE Vision Protocol (GVCP: GigE Vision Control Protocol)

GV is inherently a layer 2 communication mechanism, meaning it is designed to be used with devices connected on the same local network as MAC address' are used to communicate. In upgrading each system to cellular communications there is a crossing of networks as the data moves across the 4G or 5G networks, meaning the auto-discovery feature of GigE Vision could not be used. This prevents the host application from seeing the device to establish a connection, and therefore another solution must be implemented to combat this.

2.1.2 Network Address Translation (NAT)

Following the advice of both Profactor and the NCC Network Lead, network address translation (NAT) was chosen as the most appropriate method for enabling communication across networks. NAT is a process that involves using a unique public IP address to represent multiple devices on a private network.

The specific form of NAT used in this project is known as NAT overload, or Port Address Translation (PAT). This allows the user to go one level deeper than standard NAT and specify not only the IP address to translate but the specific ports as well. Meaning that the same IP can be used for multiple devices connected to the one router with one or multiple ports being linked to each device to allow for data flow. Figure 5 shows an example of using PAT to translate data arriving at the router IP with a specific port, to each individual device with a unique private IP associated with that port.

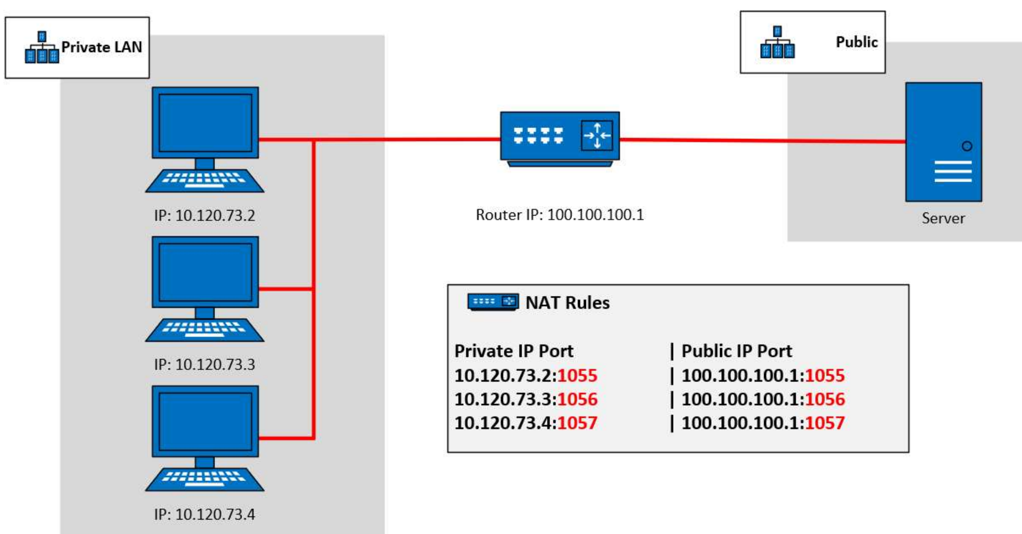


Figure 5 Port Address Translation

2.1.3 5G Demonstrator Network Architecture

Figure 6 shows the network architecture of the 5G element of this use case involving the Profactor F-Scan sensor. The sensor has two separate network interface cards (NIC); one for control and one for data, each with a separate IP address. Therefore, the sensor must be treated as two interfaces requiring specific NAT/PAT rules for each segment.

This element of the use case includes a robot that is used to position the sensor. The robot must be connected to the VM to allow for control as well as transfer of positional data to the FScan application. This is essential in ensuring the scan data has a reference of where it exists in physical space relative to the robot base.

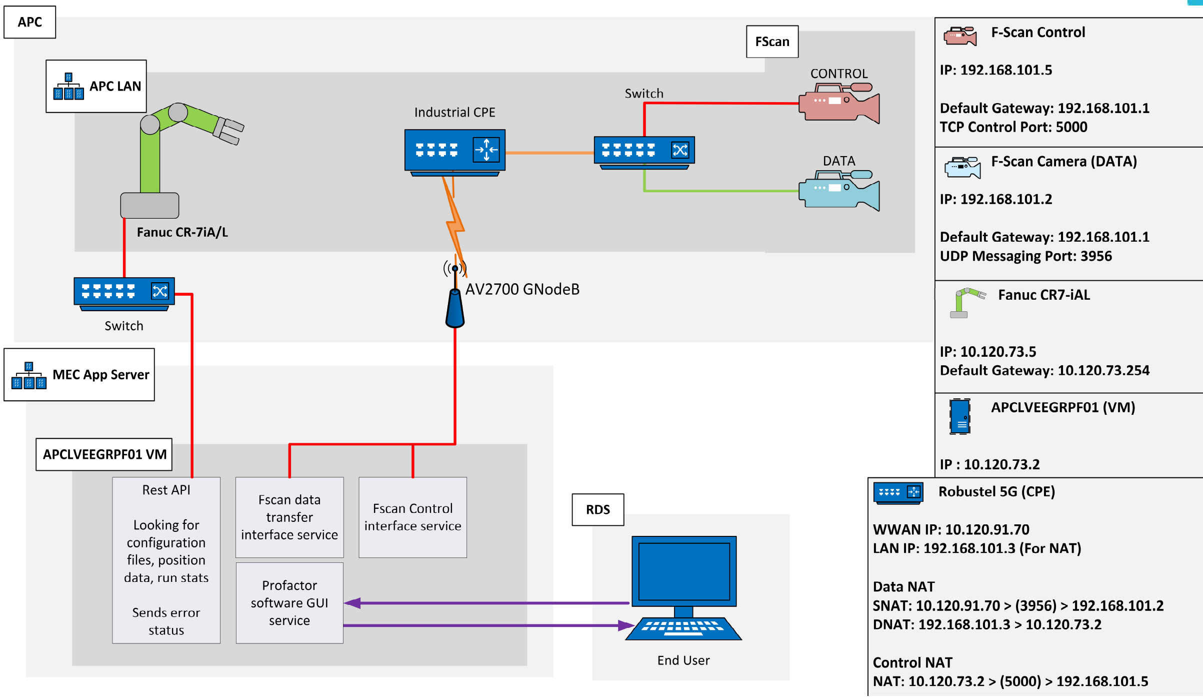


Figure 6 5G Network Architecture

As can be seen in Figure 6 both the data and control interface are directly connected to a switch, which links directly to the 5G router (CPE). This then communicates with the gNodeB radio (5G radio) to send the data back to the VM hosting the Profactor application. As the application receives the data from the sensor it processes it in near real time to give a visual output of the scanned surface that can be assessed for defects.

As previously mentioned, to achieve data flow between the VM and the sensor, port address translation is required. Figure 7 shows the communication information for the network in Figure 6 with specific IP address and ports used.

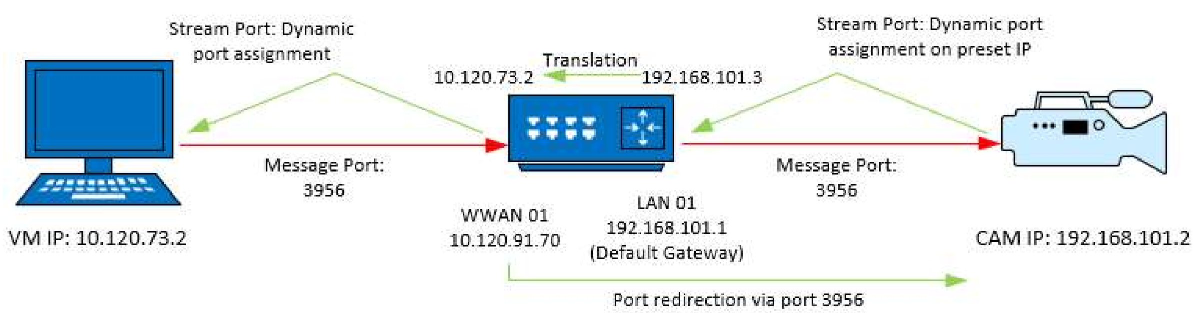


Figure 7 Port Translation for 5G Demonstrator

The application sends a discovery packet to the router on port 3956, which knows to forward that onto the camera on port 3956 using the PAT rules that are predefined. The camera receives this message and builds a data packet to return to the application which has a destination IP of 192.168.101.3 as set in the configuration file. This IP isn't associated with anything physical, however, an ARP cache entry on the router assigned this IP the same physical address (MAC) as the router (default gateway). As the GigE Vision protocol is layer 2 the data packet is sent to the physical address associated with the destination IP, which is the same as the router. The router has a NAT rule in place to translate the destination IP to that of the VM and so the application receives the data. Figure 8 shows a flow diagram explaining how the data is communicated at each step.

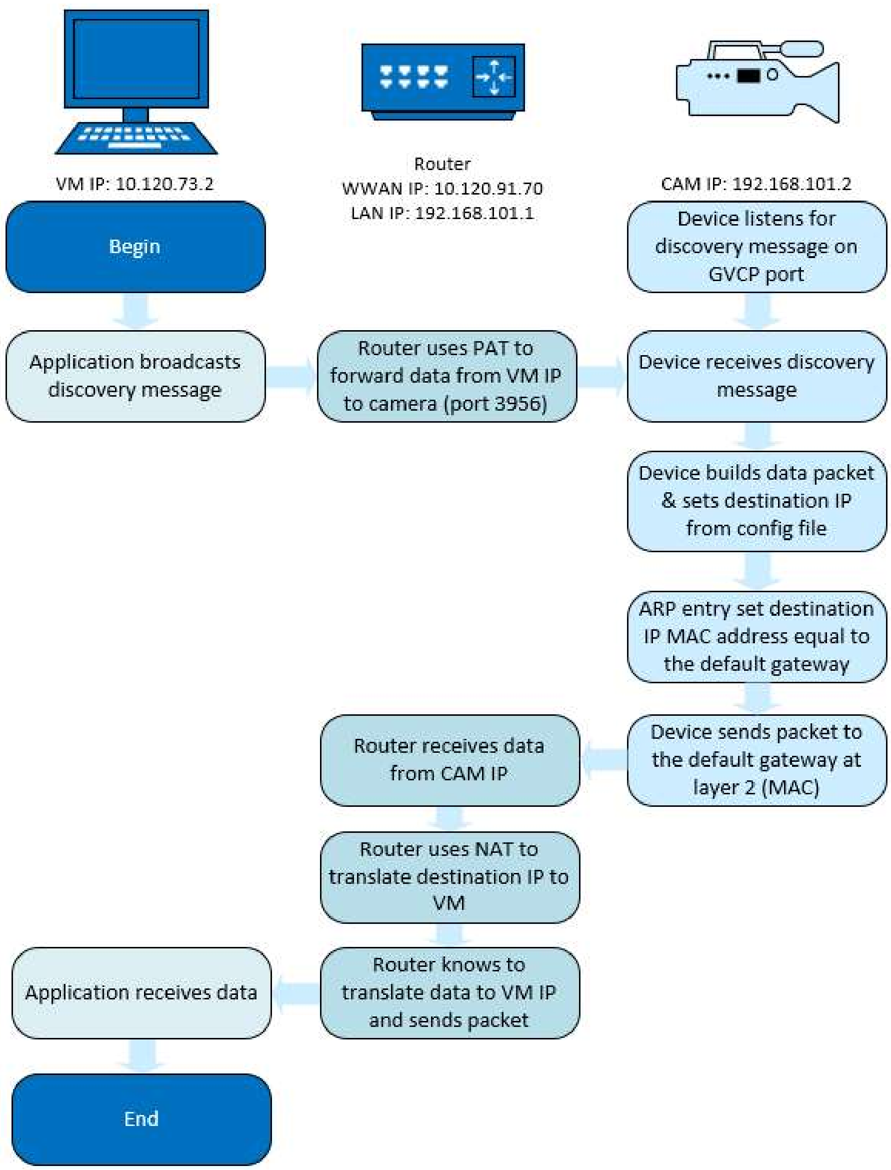


Figure 8 Data Flow Diagram

3 USE CASE DEVELOPMENT AND INVESTIGATION

3.1 Use Case Build

The original Profactor end effector provided power and data to the camera that linked directly into a high-powered PC situated on the end effector itself. Removing the Fscan sensor from the end effector means removing it from the processing PC and power supply which will therefore need to be replaced with a bespoke set up. Combined with this, the new system is designed for use with a different, much smaller robot for positioning which bring another set of challenges.

3.1.1 Fanuc CR7-iAL Cobot

The robot chosen for this task is a small Fanuc CR7-iAL collaborative robot designed for pick and place activities in parallel with a human workforce. This means that built into the robot's base is a force torque sensor that will activate the brakes whenever a peak load over a set threshold is observed. Essentially if the robot touches something it shouldn't while moving it will stop. The robot can be seen in Figure 9 and has 6 axes of motion and a maximum payload of 7Kg.

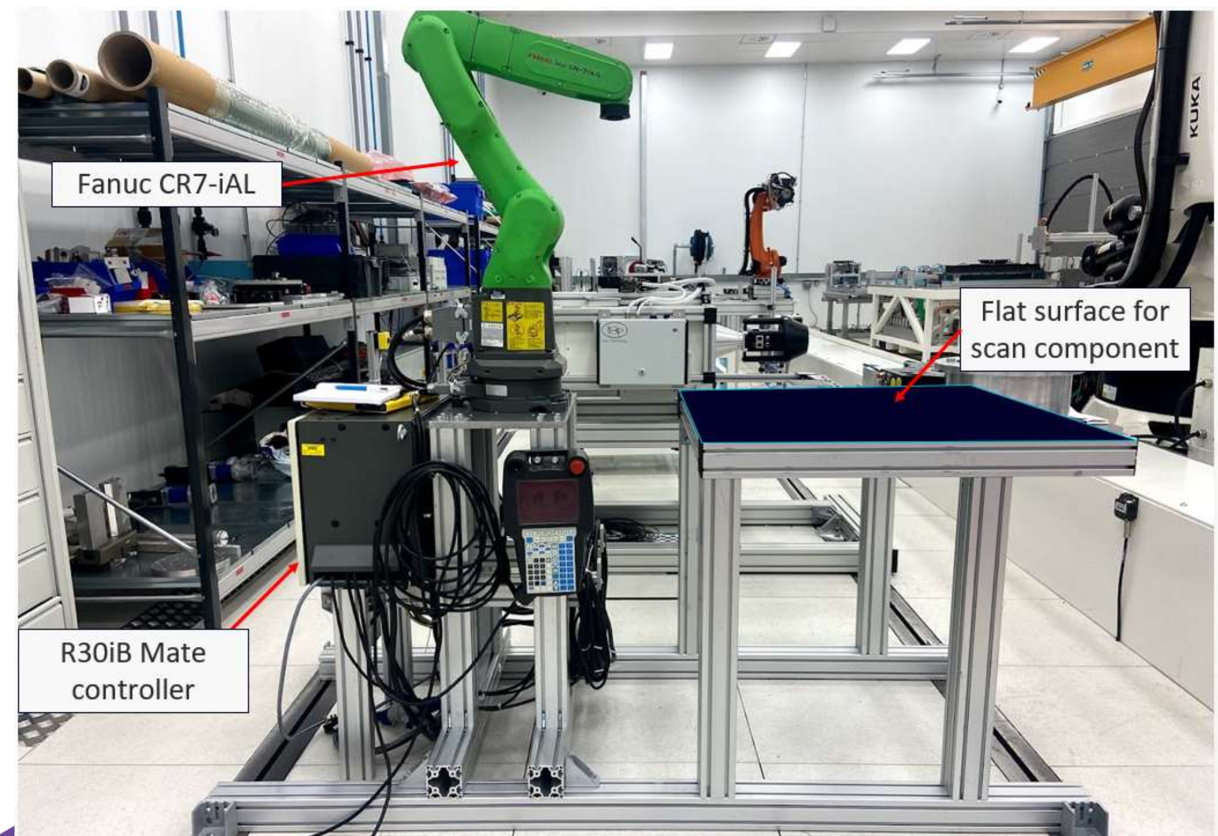


Figure 9 Fanuc CR7-iAL Cobot Set Up

This robot had not been used at the NCC up to this point and therefore required a full set up and integration into the cell before it could be used. A frame was built to position the robot off the floor and provide a structure that things can be mounted to should there be a requirement. The frame contained a mount for the Fanuc R30ib Mate robot controller and a large flat area to place the component to be scanned that can also be seen in Figure 9.

The robot controller is essential for the robot to be able to move and must be connected directly to the Profactor application to allow for both control and positional readout of the robot. The Profactor application allows the user to interact with the robot and start the scan program provided the safety circuit is complete. The decision was made to separate the robot control from the 5G network segment, to ensure the system can be safely stopped if the connection drops and control signals cannot be communicated.

To communicate between the robot and the application, User Socket Messaging was implemented on the controller which required additional input from Fanuc to install the R648 USM plug in.

Fscan_master and Fscan_server, two Fanuc specific scripts produced by Profactor were loaded onto the controller. The reason being that the original Profactor installation was designed for use with a large Kuka robot that uses a different language to communicate with the cell PLC. When Fscan_master is started on the controller by the system operator a connection is made to the application, then once the operator connects to the sensor in the application, Fscan_master starts both the scan program and Fscan_server. The scan program is what is used to position the sensor and Fscan_server is the script communicating the positional data back to the application. Figure 10 shows a simple diagram of the scripts and their linking inside the controller.

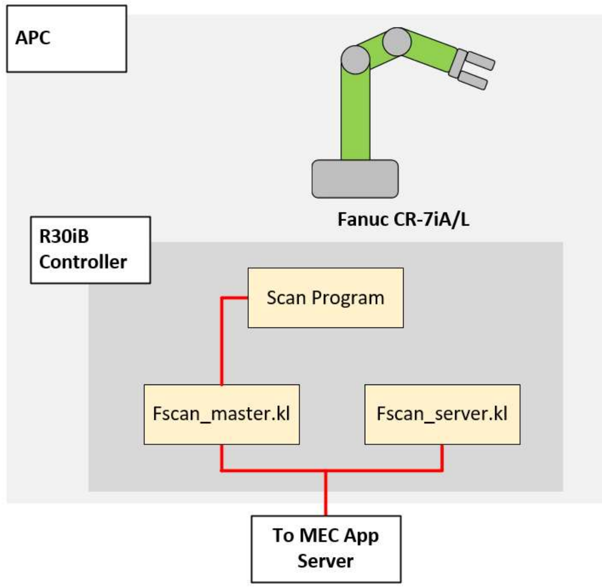


Figure 10 R30ib Mate Controller Configuration

3.1.2 Sensor-Robot Interface

Mounting the sensor onto the robot was relatively straightforward as the existing interface plate from the original end effector could be modified to fit the Fanuc. The plate consisted of 4 countersunk holes that line up with the 4 corners of the sensor, within which blots are placed that tap directly into the body of the sensor. The robot wrist has 4 x M6 tapped holes used for mounting, therefore it was a simple case of drilling 4 holes to match on the interface plate. Figure 11(a) shows the sensor in its original location attached to the interface plate, Figure 11(b) shows the interface plate mounted onto the robot.

(a) (b)

Figure 11 (a) FScan on original end effector, (b) Interface plate on CR7-iAL

3.1.3 Electrical Enclosure

As the robot has a maximum payload of 7kg there is a significant limitation on what can be held and positioned to scan components. As a result, the only thing that the robot will actually position is the sensor which weighs approximately 3.5kg, the interface plate and the cables providing power and data to the sensor itself. All other required elements of this system will be mounted to the frame in Figure 9. An electrical enclosure was produced to house the power supplies and switch required to make the system operational. Figure 12 shows a basic layout of the enclosure with each connection overlayed.

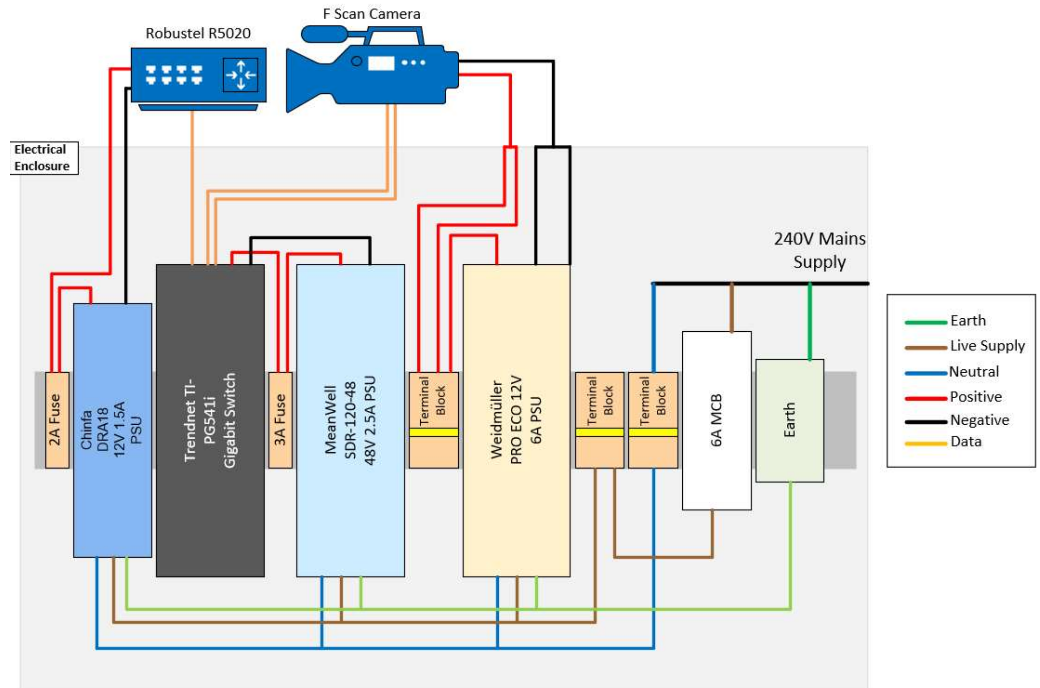
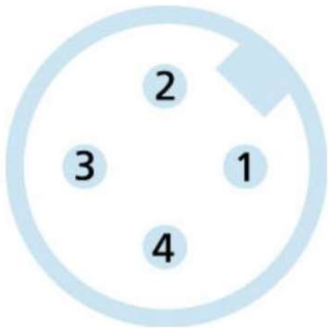


Figure 12 Electrical Enclosure

The FScan sensor has a power requirement of 12V and a peak current draw of 6A meaning this must be the provided power. To achieve this the sensor uses a 4 pin M12 power connector to act as a coupled supply as each pin has a maximum current rating of 4A. The Weidmüller 12V 6A supply in Figure 12 has two V- ports and a single V+ port meaning the output must run through a terminal block before being split off into two V+ cables to feed the sensor. Figure 13 shows the pinout diagram with the function of each pin also indicated.



Pin	Function
1	+12V
2	GND
3	GND
4	+12V

Figure 13 Power Connector Pinout

Data cables are run from the sensor into a Gigabit switch which then passes the data onto the Robustel R5020 5G router and on to the VM for processing and visualisation. The cables for both power and data were run along the length of the robot arm and into the enclosure as can be seen in Figure 14.

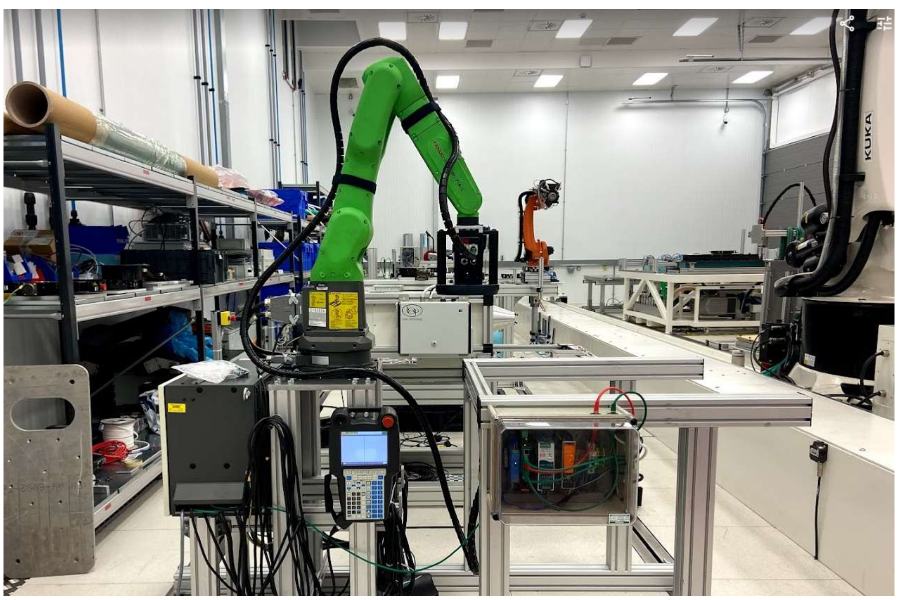


Figure 14 Sensor & enclosure mounted to robot arm

3.1.4 Virtual Graphics Processing

There is a built-in feature of the Profactor application that renders the output from the sensor in 3D, allowing the user to have a visual representation of the scanned surface. This specific feature uses OpenGL to perform the 3D rendering which requires a dedicated graphics processing unit (GPU). The server hosting the application includes two NVIDIA Tesla T4 GPUs provisioned across multiple VMs with relevant license upgrades to process and visualise the incoming data for the user. Figure 15 shows an example of a 3D rendering of a piece of woven carbon fibre than can be manipulated into any orientation to suit the user. There is an option to use the application without this feature that can be set in the json config file.

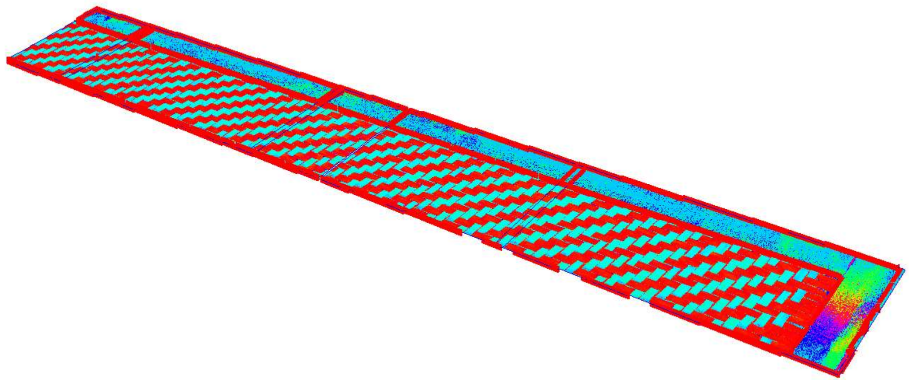


Figure 15 3D Visualisation of Scanned Surface

Should the user want to use the application without the OpenGL rendering then "hand" mode must be used. This mode only allows the user to take spot images of the surface and has no context of where it is in physical space, however, will still allow for full analysis of defects.

3.1.5 5G Integration

To make the system communicate over 5G there were a series of specific networking rules implemented on the Robustel R5020 5G router as outlined in Section 2.1.3. These are to allow traffic to flow between the VM and the camera with the presence of a GigE Vision layer 2 communication protocol. The router was mounted high up on a piece of aluminium extrusion to clear any structures that may interfere with the radio signal as shown in Figure 16.

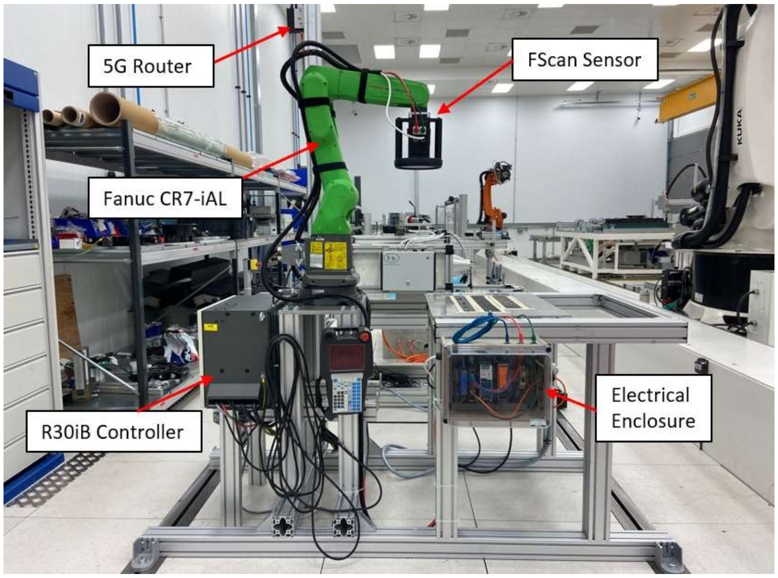


Figure 16 Completed System

3.2 Use Case Testing

In order to confirm that the system operates as expected, several tests were carried out on each aspect of the system as shown in Table 1.

Table 1 Use Case Testing Outline

Work Package	Task
Wired System Integration	Test all elements of the system individually to ensure integration is complete.
Camera testing	Test that data from the camera is communicated correctly with the Profactor application.
Robotic system testing	Test that the positional location of the robot is communicated correctly with Profactor application.
Wired Test	Perform a wired test to confirm data is transferred and processed correctly.
Application Testing	Testing graphics rendering (vGPU).
5G System Integration	Test all elements of the system to confirm everything works prior to full demonstration.

Wired system integration was carried out to ensure that all individual elements of the system were operational. This involved checking everything had the correct power being supplied, the sensor had the correct data connection, the system was patched through to the VM correctly and that everything that needed to communicate with each other could do so.

Camera testing involved ensuring that the data was reaching the correct location, and that when it did it was in the correct format. The camera inside the FScan is configured on start-up using a third-party application called eBus Player that sets the packet size and image size. This application requires a license key to remove a watermark that is linked to the physical address of the machine, which meant ensuring that the physical address of the VM was always consistent it we ever had to migrate servers.

Robotic system testing was broken down into two sections; testing the kinematic model of the robot was correct in the application, and testing communication between the application and the robot controller. The application receives the positional information from the robot in joint angles, which is then converted into cartesian coordinates based off the dimensions and rotational locations of the robot. The joint angles were confirmed to be correct within an acceptable tolerance of around 0.3 degrees, however the cartesian coordinates were incorrect. It was discovered that the robot origin uses the centre point of joint 1 rather than the centre of the base as was initially thought. To resolve this issue, rather than altering the algorithms, a simple user frame was added to the robot program that shifted the origin to the base of the robot by applying an offset in Z.

Wired system testing was carried out after all elements were confirmed to be working. Tests were carried out at varying scan speeds to investigate how the system performed as a baseline to compare the 5G system against. A strip of carbon fibre was used as the control that measured 480mm x 50mm with the sensor completing one pass across the surface. The maximum speed reached without fragmentation of the data was 300mm/s linear scan speed of the sensor with the result show in Figure 17.

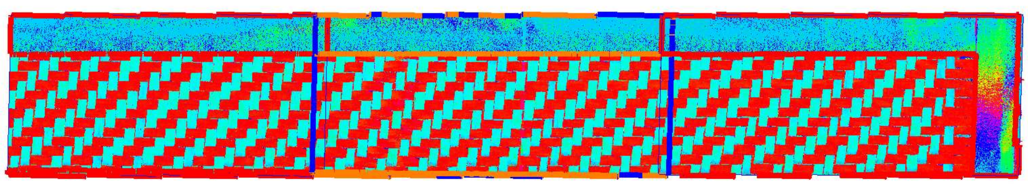


Figure 17 Scan result on wired set up

The final testing carried out involved integrating 5G into the system and confirming communication between the various elements. This was a lot more involved than initially expected as the layer 2 (physical address, MAC) framework of the GigE Vision protocol proved difficult to manipulate across a layer 3 (IP address) network. The address translation rules from Section 2.1.3 were implemented on the Robustel 5G router and the IP addresses of the sensor were altered to match.

There were several parameters that had to be altered to accommodate the 5G connection speeds that were slower than the wired set up. The linear scan speed was reduced, and the frame rate of the camera was reduced (increased frame time) to spread the volume of data being communicated over a larger time period. The frame time of the system was increased from 2200μs to 100,000μs with the linear scan speed reducing from 300mm/s to 1.5mm/s before no fragmentation was observed.

3.3 Use Case Discussion

By referring to the project requirements set out in Sections 1.4.1 & 1.4.2 an understanding of use case success can begin to be developed.

Comparing against functional requirements:

- The function of the sensor system remains unchanged when comparing to the original deployment. Both systems use the same application to process and visualise the data with no loss of functionality, capable of collecting the same information regardless of host location.

- The updated system interfaces fully with the Fanuc CR7-iAL collaborative robot, positioning the sensor over the desired component and providing accurate positional readout to the application for spatial reference. The collaborative robots' ability to work alongside a human workforce safely without the need for additional safety allows for integration into existing manual processes, however, the robot has a reduced reach when compared to the original deployment.

- The robustness of the system is difficult to quantify, however, one could argue that a simplified system designed for a specific application is less likely to fail as there are fewer elements to go wrong. A simplified robot system performing a dedicated function with a dedicated connection and power source is not only easier to troubleshoot but easier to maintain. The virtual server can be easily reconfigured from a previous disc image should anything go wrong, whereas with the original deployment a physical PC must be manually maintained or replaced.

Comparing against the non-functional requirements:

- The 5G radio installed within the APC cell had sufficient power and coverage so that the sensor system could be positioned anywhere in the cell and achieve the same network characteristics. The sensor system was positioned as far from the radio as possible (~20m) to demonstrate this, however, this was the maximum range tested within this use case as, once the assembly was built it was not removed from the cell.

- The coverage within the rest of the factory was sufficient to run other use case applications with similar observed network performance, and therefore an assumption is made that where there is signal, this use case would be operational.

- The latency observed in both uplink and downlink was capable of near real time processing and allowed the sensor control signals to perform as expected. The 5G network was however not capable of providing a connection comparable to that of the original wired deployment, and the use of jumbo frames again was not possible.

Specific 5G element of this use case are evaluated in more detail in Sections 4 & 5.

3.4 Use Case Conclusions

The use case outlined in this report shows significant progress against the objectives set out in section 1.2.1. Comparing the finished system against the project objectives it is clear to see that this use case has been successful in demonstrating the benefits of designing with digital capability in mind.

- By using edge compute to centralise the processing power of the system, the end effector could be significantly reduced in size and weight as the PC is no longer present, leading to a weight reduction of 40kg.
- Virtual graphics processing removes the need for compute power on the device being used for visualisation, meaning any device capable of remote desktop connection can interrogate scan results in 3D.
- Reduction in end effector footprint has allowed a significantly smaller robot to be used, reducing the robot system cost by 88% & integration cost by 98%.
- Reduction in end effector footprint has increased the capability of the system by allowing tighter geometries to be scanned (~1.2m x 1.2m x 0.3m versus ~0.2m x 0.2m x 0.3m)
- 5G enablement means the system can be deployed anywhere that has power and signal, increasing the flexibility of the system.

4 5G INDUSTRIAL ASSESSMENT

4.1 4G and 5G Network Testing

This section will focus on the specifics of the cellular networks used in this use case and the testing involved to assess their performance.

4.1.1 4G Feasibility Study

This project used a private 4G network installed at the NCC to assess the feasibility of this use case and create a cellular performance baseline. A simple NCC built data capturing system was upgraded to cellular communication using 4G LTE to investigate if GigE Vision could be made to work over a layer 3 network. 4G LTE has a maximum theoretical uplink/downlink of 50Mbps & 150Mbps respectively while 5G has a theoretical uplink/downlink of 1Gbps & 10Gbps+ respectively. Therefore, it is not expected that the 4G element will work perfectly, but highlight the benefits of 5G over 4G LTE for a similar application, and to gain early lessons on migrating from wired to cellular wireless technology.

The system chosen was the Composite Quality Capture System (CQCS), a simple data capturing tool shown in Figure 18, that uses a MicroEpsilon laser line scanner to determine out of plane defects such as missing plies and gaps, combined with a FLIR vision camera used to capture high quality images of the surface. The system was developed purely as a data collection tool and does not possess any form of verification algorithm, with data captured and stored against a digital passport of the material/component.

Figure 18 CQCS - MicroEpsilon Laser Line Scanner (Left) FLIR Vision Camera (Right)

Figure 19 shows the network architecture that was employed for the 4G element of this use case on the CQCS. Each sensor was connected directly into an industrial CPE (4G router) with specific NAT rules applied for each device to allow communication across networks. Each CPE communicates with the 4G radio (eNodeB) that is patched directly back to the Evolved Packet Core (EPC). The EPC integrates the incoming 4G LTE data into the IP network behind it and onto the specific virtual machine hosting the software elements of each sensor, thus allowing for data flow between the server and the sensors in the workshop.

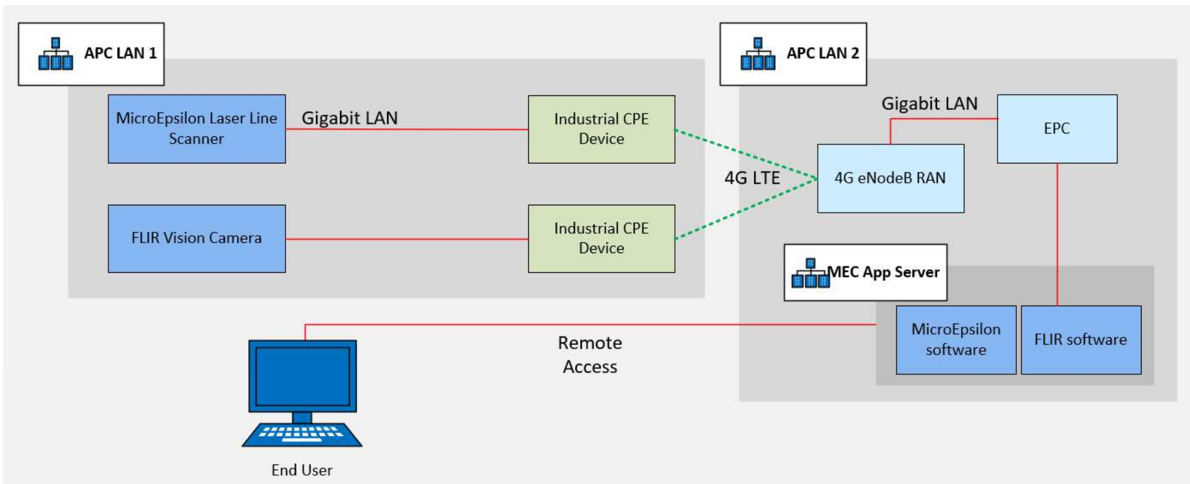


Figure 19 4G Network Architecture

The system had been designed to be used with the hardwired data network within the APC, therefore modifications were made to enable 4G communication. An additional enclosure was added that housed two 4G routers, each connected to one of the sensors in the array.

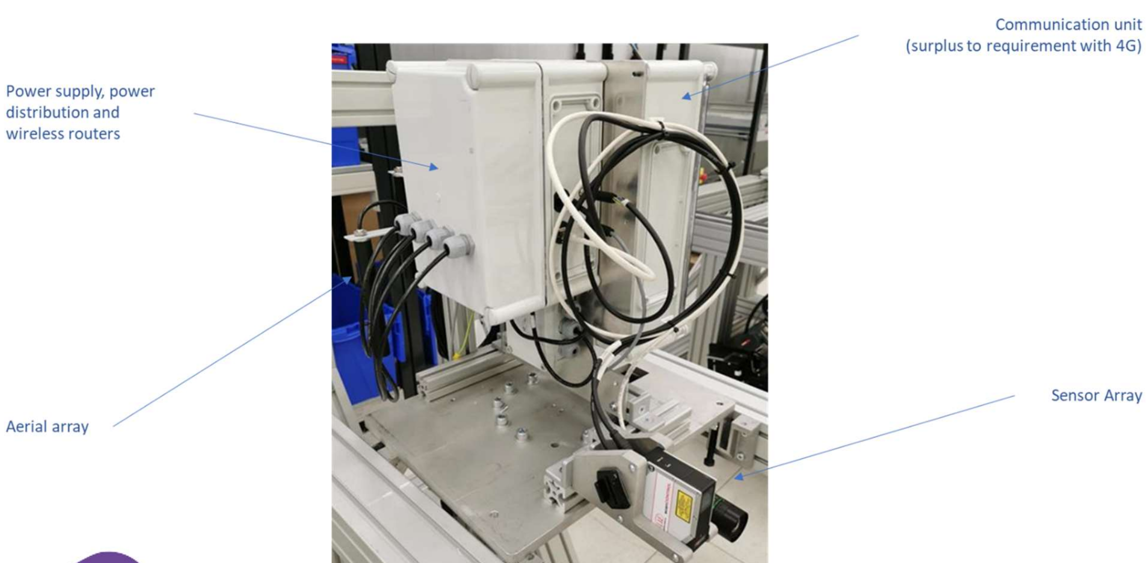


Figure 20 4G Enabled CQCS End Effector

Figure 20 shows the finished system. Each 5G router had a requirement for two omnidirectional antennas to be mounted on the rear as can be seen by the 4 grommets protruding from the side of the box marked “Ariel Array”.

As this system was not designed with any image processing capability there is no need to remove a bulky PC from the assembly, however, edge compute power was still required to host the relevant software for each sensor.

To make use of NAT to cross the different local networks, each sensor was given a fixed IP address. Of the two sensors in question, only the laser line scanner allowed the user to specify an IP address for the device, therefore, to receive data from the FLIR vision camera a third-party application was required, in this case RoboRealm.

4.1.2 4G Outcomes/shortfalls

Both devices contained within the CQCS; the Micro Epsilon laser line scanner and the FLIR vision camera, were connected successfully over the 4G network and data was successfully communicated between them and the virtual machine hosting the software applications.

The private 4G network installed at the NCC could reach speeds at the time of testing of up to 30Mbps (3.75MB/s) on downlink and 10Mbps (1.25MB/s) on uplink. Before the work was carried out it was clear that the 4G speeds were not sufficient for the system to run at its full potential, however the latency also required validation. Ping tests were conducted to get a measure of latency from the VM to the FLIR camera on the CQCS, and over 19 pings an average latency of 155ms was recorded with a maximum of 1372ms and a minimum of 40ms. This latency may be acceptable for applications that do not require real time processing, but for an application using a robot to position a sensor that updates every 10-12ms this is not sufficient.

While 4G LTE may not have been fast enough to run this process at its full potential, it does prove that this architecture is feasible, as well as providing some useful data to compare future technologies against. Validating this architecture using 4G shows that GigE Vision as a protocol can be manipulated to traverse networks and paved the way for the 5G demonstrator. There may be more scope to investigate the full potential of 4G LTE for this application in the future, however, after proving the connection is possible the focus was shifted to the 5G set up.

4.1.3 5G Test Setup

The 5G network architecture for the Profactor system was built on a similar network framework to the 4G set up, and while the speeds were not the maximum that 5G can offer they were significantly faster than the 4G. The private 5G network installed at the NCC was capable at the time of testing of reaching up to 400Mbps (50MB/s) on downlink and 57Mbps (7.125MB/s) on uplink. Regardless, this value of uplink data rate is far from the 900-1000Mbps required for the sensor to operate at full capacity.

Initially tests were conducted at the same parameters as the wired baseline outlined in Section 3.2, however, the results were poor with little to no useful data being seen on the VM. The throttled uplink speed meant that the network couldn't handle the volume of data that was being pushed up to the server, and some reconfiguration of the sensor was required. The MTU size was reduced from 9016K down to 1444K to relieve the pressure on the connection as the application was reporting a large number of skipped frames. The initial scans using the jumbo frames caused a large amount of data fragmentation with only parts of the scan being visible in the application as shown in Figure 21. This fragmentation of data seemed to cause some issues with network stability and would regularly require a reboot following a bad scan.

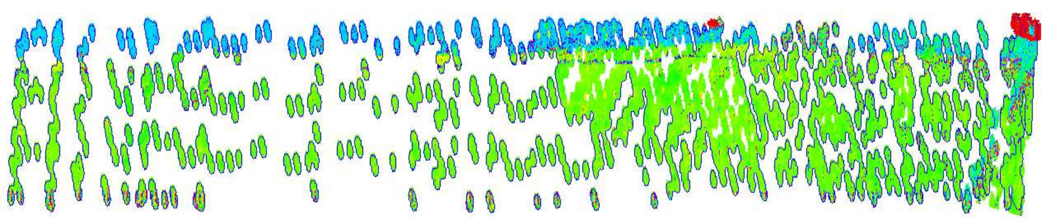


Figure 21 Data fragmentation over 5G

By reducing the MTU size, slowing down the linear scan speed of the robot and reducing the framerate of the sensor, the volume of data being sent to the server was spread over a greater time and the number of skipped frames significantly reduced. The result was a complete scan as shown in Figure 22.

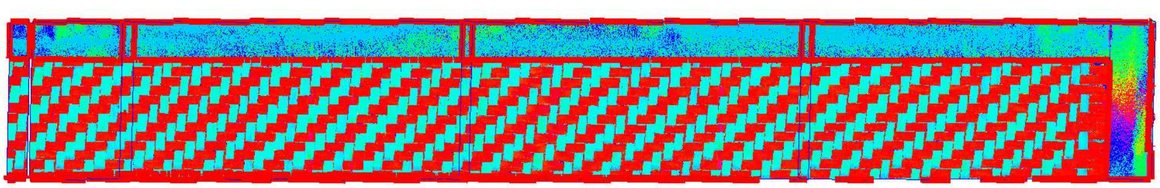


Figure 22 Complete Scan over 5G

4.1.4 5G Metrics

During testing of the 5G system, network metrics were gathered to give an indication of how the network behaved. The metrics themselves were gathered from the Airspan radio software (5G provider), over periods of 15 minutes. Each scan over 5G took approximately 5.5 minutes and therefore the values are not completely representative but give a good indication of network behaviour. The metrics of most interest to this use case are the latency and throughput performance, on uplink rather than downlink due to the nature of data generation. As outlined in Section 1.3.3, latency is a measure of how long it takes packets to be sent and received and throughput is a measure of data rate.

Figure 23 is a graph showing the uplink throughput of the distributed unit that serves the specific radio this use case is connected to. A total of 8 spikes can be seen that coincide with the 8 tests that were carried out (includes successful and unsuccessful).

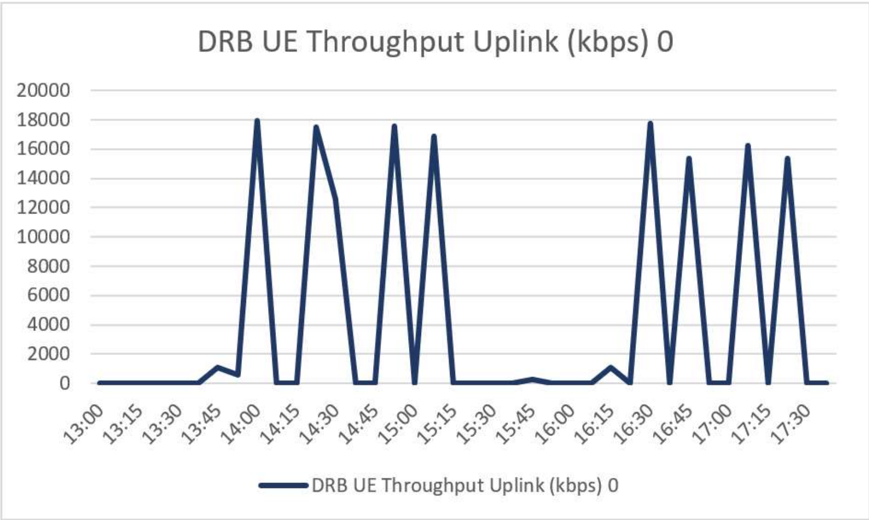


Figure 23 5G uplink throughput

A throughput of ~18Mbps (18000Kbps), can be seen from the graph which would indicate a data rate of 2.25MBps (18000/15 = 2.25). The real-world throughput may have been higher than this however, as these values are averaged over the total 15-minute period and include periods of no data transfer.

A metric that can be used in conjunction with the observed throughput is the Physical Radio Block (PRB) usage percentage. PRB usage is the amount of available radio resource. Comparing the PRB usage % on both uplink and downlink and we can begin to see the network consumption of this application.

Figure 24 shows the PRB usage % on uplink during the testing period. Comparing this to Figure 25 which shows the downlink PRB usage % and it is clear to see the difference. The use case consumes ~70% of available uplink while only consuming ~5% of available downlink.

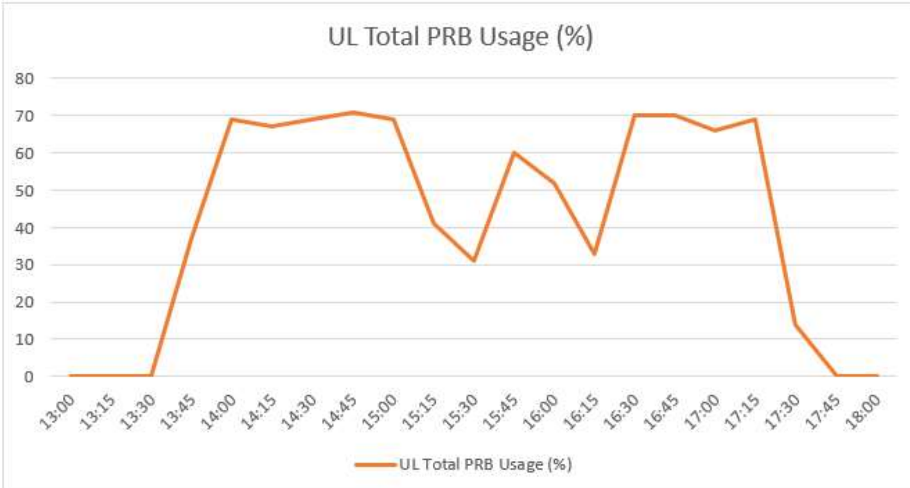


Figure 24 5G PRB usage on uplink

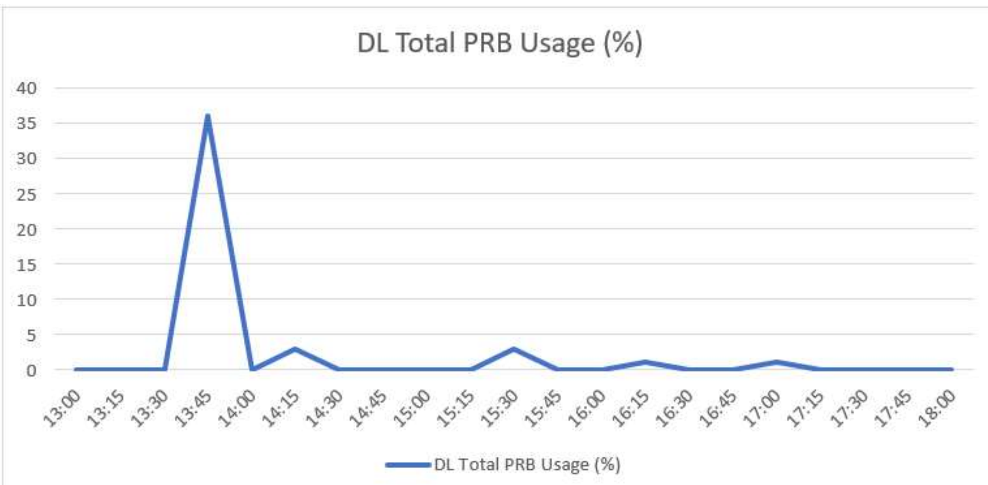


Figure 25 5G PRB usage on downlink

The PRB usage % comparison confirms the need for significant uplink throughput for this application and would indicate the need for more appropriate network balancing. In its current form this 5G network can only support one sensor system per radio; any additional systems and it would cause the network to overload.

Latency testing was carried out in a similar manner to the 4G testing. A total of 100 pings were sent between the VM and the sensor with an average of 14ms, a maximum of 164ms and a minimum of 11ms being recorded. These values are a significant improvement on the observed values from the 4G testing and are not far outside an ideal region (10ms) for this application.

Network stability was also of interest as during some scans the connection would drop completely and would require a reboot of the CPE before it re-attached. Figure 26 shows the unplanned release requests that occurred during the testing period with 4 observed between 13:45-14:00 and a further 2 observed between 14:00 – 14:15. The cause of these is not known, only that it was unplanned. This, however, does prove the presence of some network instability in either the radio or the CPE around the time of testing with high data fragmentation. The unplanned releases can be seen to cease as the scan speed was reduced and MTU size adjusted for the reduced connection speeds.

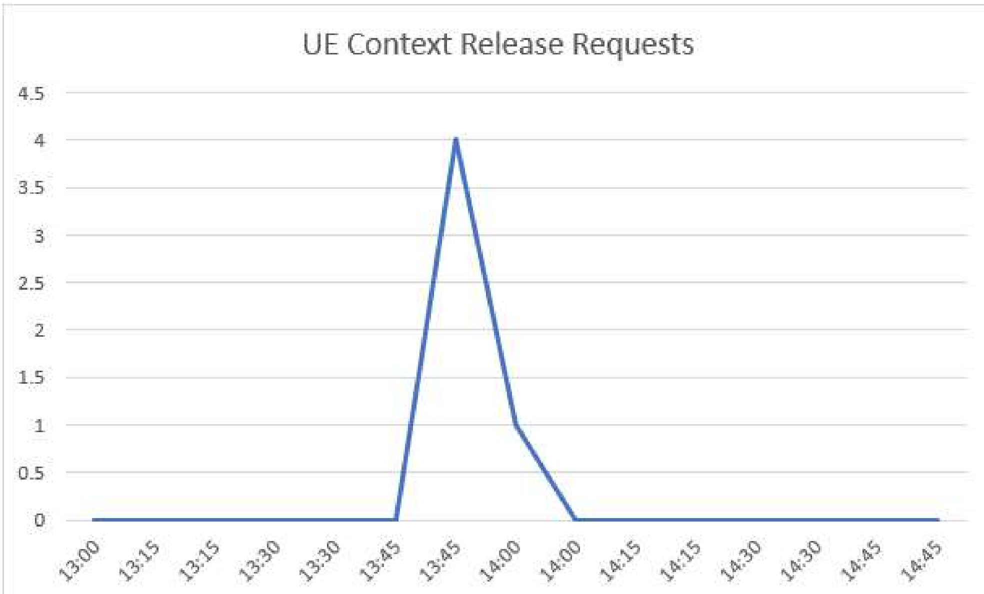


Figure 26 Unplanned session releases

5 5G DISCUSSION

5.1 Benefits of 5G

The benefits that 5G as a technology can bring to smart manufacturing have been partially demonstrated in this use case but regardless, as the technology matures there is no doubt of the potential improvements 5G can bring.

The flexibility of deployment that 5G can add to a factory, coupled with the vast number of interconnected devices that can simultaneously link back to the same core means that 5G as a technology will surely aid in accelerating toward Industry 4.0. Having infrastructure in a factory interconnected, but not restricted with hardwired data connections mean the level of flexibility increases dramatically. Being able to alter the layout of a factory without the need to alter the infrastructure behind it means both the cost and time associated with setting up a new or novel process are dramatically reduced.

In upgrading the sensor system to 5G this concept of data transfer has been proven. While the speeds may not have been what was expected, the communication of large volumes of data across a private 5G network have been demonstrated. In turn allowing for a powerful system to become more accessible and deployable.

5.2 Limitations of 5G

Some limitations of this technology have been clearly highlighted by this application. The lack of uplink speed meant that the scan was 200 times slower than the baseline. Also, intermittently, during periods of high data transfer (>70% of available uplink bandwidth), the CPE device would indicate a connected state although data transfer had ceased and rendered the device unusable. Testing concluded that data transfer issues were prevalent on the specific device attached to the radio and not the radio itself. Further investigation indicated that when the device data transfer ceased, irregular core flows were observed within the RAN software specific to the radio in question, therefore proving the CPE device was not operating as expected. Root cause for this issue has still not been fully identified but this behaviour has been observed across multiple CPE devices from multiple manufacturers (all CPE devices leveraged the same 5G microchip). Remediation of this issue involved a soft reboot of the CPE device, which led to a successful reattach to the 5G packet core and data transfer resumed.

Another major challenge in upgrading this system to 5G was the presence of the GigE Vision industrial protocol. This protocol is widely used for applications that produce large amounts of data but has always been limited to devices on the same local network. Enabling communication of a layer 2 GigE Vision device across a layer 3 network required a deep understanding of the process in which data is transferred. Without the presence of a highly skilled network engineer is it unlikely this process would have been possible and could therefore be a blocker to this being more widely adopted into industry.

5.3 5G Conclusions

5G testing showed the difference in requirement between uplink throughput and downlink throughput for this application, and the PRB usage % indicated the need for increased uplink throughput and improved network balancing. As a result of the observed network performance, scan parameters had to be adjusted to ensure the output was of use. The framerate of the sensor, the MTU size, and the linear scan speed of the robot were all significantly reduced to prevent any fragmentation of data.

The knock-on effect of this was that the scan speed over 5G was approximately 200x slower than when compared to the wired baseline. Therefore, it is fair to say, in its current state the installed 5G network at the NCC, while functional, is not sufficient to make this a superior method of transferring data when compared to a wired set up. 5G, however, is a very infant technology and as with all things, greater understanding leads to greater performance. As the software behind the 5G deployment matures, the capability of the technology will improve, and with an upgrade planned for January 2022 that promises to increase the observed connection speeds, this improvement may come sooner than expected.

To conclude, this use case has been an overall success. The project objectives of demonstrating how digitisation and 5G can lessen the barriers to more widespread acceptance into industry have been met. Reductions in robot system costs, integration costs and deployment costs have all been observed and an architecture has been designed to connect layer 2 (MAC) devices over a layer 3 (IP) network. It should be noted that until a 5G specific industrial standard for high throughput applications is developed, GigE Vision will continue to add complexity to upgrades of this nature.

6 APPENDICES

6.1 APPENDIX A – Reduced Integration Cost Detail

It must be noted that the original deployment of the Profactor verification rig within the APC was an addition to an existing cell. The costs shown are that of the elements of the cell that are required for the original system to operate. The use case costs are independent of this as they do not make use of this existing hardware.

Item: Original Deployment	**Cost (£)**
Fixture Kits	37,818
Cell Control system (safety, monitoring, control software)	68,570
Cell Control System – Electrical Cabinets	69,303
Installation	96,068
Total	**271,759**

Item: Use Case Deployment	**Cost (£)**
Electrical Cabinet	1,516
Extrusion (£16/m)	160
Installation & Commissioning (50h x 75£/h)	3,750
Total	**5,426**

% Of Original Cost	**1.99**

6.2 APPENDIX B - Reduced Robot Cost Detail

Item: Original Deployment	Cost (£)
Kuka KRC510	70,967
ATI Omega Force Torque Sensor	23,900
Track system	66,528
Tool Changer	19,185
Total	**180,580**

Item (Updated)	Cost (£)
Fanuc CR7-iAL	22,091

% Of Original Cost	12.23

6.3 APPENDIX C - Reduced Deployment Cost Detail

Original APC Breakdown	Cost (£)
Integration	271,759
Robot system	180,580
Total	**452,339**

Total UC Cost Breakdown	Cost (£)
Integration	5,426
Robot system	22,091
NCC Support (200h x 75£/h)	15,000
Profactor Support	11,150
Total	**53,667**

% Of Original Cost	11.86