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A 5G Automated Guided Vehicle SME Testbed for Resilient Future Factories

DANIEL S. FOWLER, YUEN KWAN MO, ALEX EVANS, SON DINH-VAN, BILAL AHMAD, (Senior Member, IEEE), MATTHEW D. HIGGINS, (Senior Member, IEEE), CARSTEN MAPLE
WMG, The University of Warwick, Coventry, CV4 7AL, UK

Corresponding author: Daniel S. Fowler (e-mail: dan.fowler@warwick.ac.uk).

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ABSTRACT Factory automation design engineers building the Smart Factory can use wireless 5G broadband networks for added design flexibility. 5G New Radio builds upon previous cellular communications standards to include technology for "massive machine-type communication" and "ultra-reliable and low-latency communication". In this work, the authors augment an automated guided vehicle with 5G for additional capabilities (e.g., streaming high-resolution video and enabling long-distance teleoperation), increasing the mobile applications for industrial equipment. Such use cases will provide valuable knowledge to engineers examining 5G for novel smart manufacturing solutions. Our 5G private network testbed is a platform for wireless performance research in industrial locations and provides a development mule for flexible smart manufacturing systems. The rival wireless technology to 5G in industrial settings is Wi-Fi and it is included in the testbed. Furthermore, the authors noted challenges, often unconsidered, facing the move to digital manufacturing technologies. Therefore, the authors summarise the emerging challenges when implementing new digital factory systems, including challenges linked to societal concerns around sustainability and supply chain resilience. The new Smart Factory technologies, including 5G communications, will have their roles to play in alleviating these challenges and ensuring economies have resilient future factories.

INDEX TERMS 5G mobile communication, AGV, AMR, CPPS, cyber-physical systems, industrial strategy, integrated manufacturing systems, resilience engineering, smart manufacturing.

I. INTRODUCTION

GOVERNMENTS view industry and innovation as foundational for a strong economy [1]. Innovation leads to new products for manufacturers and improvements in manufacturing efficiencies and cost reductions. The adoption of *smart manufacturing* provides industrialists with new tools to further improve their manufacturing processes. Smart manufacturing is a "method that improves its performance with the integrated and intelligent use of processes and resources in cyber, physical, and human spheres to create and deliver products and services, while also collaborating with other domains within an enterprise's value chains" [2].

One of the technologies targeted at aiding the implementation of smart manufacturing is Fifth Generation New Radio (5G NR) communications, simply known as 5G, a cellular broadband telecommunications standard. 5G builds upon the previous generations of cellular communications technology to improve data transmission capabilities and define new use cases [3], [4]. This allows industrial stakeholders to consider novel smart manufacturing applications and new process configurations.

5G and its industrial applications are an active area of research [5], [6] with large industrial organisations testing its capabilities. What is not clear is whether Small and Medium-sized Enterprises (SMEs) will be able to benefit from 5G in a cost-effective way. Growth in the take-up of advanced wireless communications within factories requires knowledge of what can be achieved in system implementations, and practical evidence of 5G's benefits to future factory systems. That knowledge and evidence can be gained from 5G testbeds [7]. Here, the developed testbed use case is the augmentation of an Automated Guided Vehicle (AGV) with 5G with the option to switch to Wi-Fi. The AGV utilises the characteristics of 5G's advanced wireless communication technology to allow for testing improvements in wireless data connectivity within industrial environments.

Introducing smart manufacturing technologies into factories does raise some challenges. This work re-examines some of those challenges as it was seen that they are not always addressed in the smart manufacturing literature. 5G communications can be used to help address those challenges for future factories. Some of the challenges go beyond the level of any deployed *smart* production systems as governments are looking at industry to be resilient to global economic and environmental pressures and contribute to sustainability aims which are highlighted within the United Nations 17 Sustainable Development Goals (SDG) [8]. Advanced wireless communications will have a role to play in improving manufacturing systems to help address those sustainability aims.

The sections below begin (Section II) with a background to the work and the motivations to build an AGV testbed to study the implementation and use of 5G within manufacturing. The ideas behind the Industry 4.0 concept, a driver for smart manufacturing, are briefly revisited (II-A). A summary of the range of smart technologies being applied to manufacturing applications is provided (II-B), listing some of their advantages. 5G wireless communications (II-C) is summarised, and the new functionality that is useful to manufacturing applications (II-D) covers some challenges in 5G manufacturing implementations. The 5G AGV testbed use case is described in Section III, it includes a summary of previous 5G AGVs (III-A), the WMG testbed (III-B), some considerations on 5G vs Wi-Fi for SMEs (III-C), and the WMG testbed in operation (III-D). The discussions in Section IV examine the use cases for the testbed (IV-A) and includes some challenges that implementing smart manufacturing technology can bring (IV-B). The renewed interest in manufacturing resilience is examined (IV-C) along with the role 5G may play in adding resilience to smart future factories (IV-D). The work concludes in Section V. Table 1 provides a summary of the abbreviations and terms used in this work.

TABLE 1. Abbreviations and terms in this work

Abbrev./Term	Meaning
4G	Fourth-generation cellular telecommunications
5G	Fifth-generation cellular telecommunications
AI	Artificial Intelligence
AMPS	Advanced Mobile Phone System
AMR	Autonomous Mobile Robot
AGV	Automated Guided Vehicle
AR	Augmented Reality
BCMS	Business Continuity Management Systems
C&C	Command and Control
CAD	Computer Aided Design
CAM	Computer Aided Manufacturer
CDMA	Code Division Multiple Access
CN	Core Network (or simply *Core*)
CNI	Critical National Infrastructure
CPPS	Cyber-Physical Production System
CPS	Cyber-Physical System
D-AMPS	Digital AMPS
DT	Digital Twin
eMBB	Enhanced Mobile Broadband
eNodeB or eNB	Evolved Node Base station (4G)
EPC	Evolved Packet Core (packet core for data and voice)
eSIM	Electronic SIM
FMS	Flexible Manufacturing Systems
gNodeB or gNB	Generalised Node Base station (5G)
GSM	Global System for Mobile
HSPA	High Speed Packet Access
I4.0	Industrie 4.0 (Industry 4.0)
IIoT	Industrial Internet of Things
IS-95	Interim Standard 95
IMSI	International Mobile Subscriber Identity
IMT	International Mobile Telecommunications
ITU	International Telecommunications Union
IT	Information Technology
KPI	Key Performance Indicator
LARG	Lean, Agile, Resilient, and Green
LiDAR	Light Detection and Ranging
LoRaWAN	Long Range Wide Area Network
LTE	Long Term Evolution (data packet cellular comms)
MES	Manufacturing Execution System
MiR	Mobile Industrial Robots (a company)
ML	Machine Learning
mMTC	Massive Machine Type Communications
mmWave	Millimetre wave
NV	Network Virtualisation
NR	New Radio, i.e., 5G NR
NSA	Non-standalone
NTC	Nordic Mobile Telephony
OT	Operation Technology
PDC	Personal Digital Cellular
PLC	Programmable Logic Controller
QoS	Quality of Service
RAMI4.0	Reference Architecture Model Industry 4.0
RE	Resilience Engineering
RF	Radio Frequency
SA	Standalone
SIM	Subscriber Identity Module
SIMPLE	Smart Information Platform and Ecosystem
SDG	Sustainable Development Goals
SDN	Software Defined Network
SME	Small and Medium-sized Enterprises
SMS	Short Message Service
TACS	Total Access Communication System
UE	User Equipment (a wireless device)
OPC UA	Open Platform Communications Unified Architecture
URLLC	Ultra-Reliable and Low Latency Communications
UMTS	Universal Mobile Telecommunications System
USB	a Universal Serial Bus
VR	Virtual Reality
WCDMA	Wideband Code Division Multiple Access
Wi-Fi	Wireless Fidelity (the IEEE 802.11 family)

II. MOTIVATION AND BACKGROUND

Manufacturers have always embraced technology to help with the complexities of production, process control, delivering output and managing supply chains. Wireless communication is one of the technologies available for deployment in factories, and manufacturers can look at the capabilities of 5G and advanced Wi-Fi (versions 6 or 6E and the upcoming version 7) to add new abilities to their production systems and enhance existing processes. This work is motivated by the fact that AGVs in 5G networks have seen little use and study. This has been highlighted in previous work [9]. Further, there is a need to examine the claimed advantages and understand technical considerations when deploying 5G in smart manufacturing environments. Using the AGV testbed will identify the challenges that automation engineers will face in 5G system implementations and whether the claims made for the technology are reliable. This is particularly important for resource-limited SMEs whose growth could be affected if investments in systems do not meet expectations.

Moving beyond the technical challenges of deploying new smart manufacturing technology, there are risks around the safety, security, and life cycle management of a deployed system. These risks can be viewed as a variety of potential *disruptors* that may weaken production output despite the smart technology deployment. To mitigate the effect of disruptors strategies can be used to add resilience to any form of system. How smart manufacturing technologies intersect with aspects of systems resilience is an area of research that testbeds can support. Since there is a link between the resilience of deployed smart manufacturing systems and the overall industrial domain resilience (mentioned in the Introduction), the work examines the aspects of resilience applicable to future factories and their deployed smart technologies.

A. REVISITING THE OBJECTIVES OF INDUSTRY 4.0

The *Industrie 4.0* initiative, Industry 4.0 or simply I4.0, was a recognition by Germany that the technologies enabling the emergence of smart factories could threaten their position as a leading manufacturing country [10]. In I4.0, the manufacturing process is integrated into a network of connected Cyber-Physical Systems (CPS) used to optimise the entire supply chain, from initial order to final delivery. Every step that enables a product or service to be designed, produced, and delivered is instrumented to enable large amounts of data to be analysed and acted upon. This enables fine-tuning of these Cyber-Physical Production Systems (CPPSs) [11] for maximum efficiency, minimum cost, flexibility, and zero downtime. Online ordering and delivery to consumers via sophisticated logistics systems are well established, having benefited from advances in technology and software. The deployment of the Industrial Internet of Things (IIoT) is seen as a similar enabler for I4.0. Some of the facets that I4.0 is seen to provide include:

- Data feeds from high-density embedded sensor networks.
- Granular identification of products, their location and history.
- Autonomous machine-to-machine communication and control.
- High levels of integration between all processes and management information systems.
- Application of data analytics, machine learning and other artificial intelligence techniques.
- Efficiency gains in material usage, resources, and energy consumption.
- Improving the lifecycle management of assets, including improvements in preventive maintenance.
- Real-time management of dispersed processes and their environments, reducing time lags between processes and events.
- Support for on-demand highly customisable products and services.
- Reducing environmental impact.
- Reduced use of humans for routine tasks, improving their working environment.

A variety of the above facets of I4.0 are seen in the new smart manufacturing systems that new digital technologies are enabling.

B. A BRIEF OVERVIEW OF NEW SMART MANUFACTURING TECHNOLOGIES

There is a diverse range of technologies that can be encapsulated within the realm of smart manufacturing [13]. These include:

- Advanced digital-based manufacturing
- Industrial Internet of Things (IIoT) and smart sensors
- Big data analytics and visualisation
- Machine Learning and Artificial Intelligence
- Containerisation and virtualisation of apps and services
- Digital Twins (DT)
- Advanced wireless communications (5G/Wi-Fi 6/LoRaWAN)
- Software Defined Networks (SDN)
- Autonomous robots, cobots, and teleoperation
- Augmented Reality (AR) and Virtual Reality (VR)
- Cloud computing
- Additive Manufacturing

This list of digital technologies undoubtedly brings many possibilities and advances to manufacturing systems, however, it raises new challenges for the industrialists that want to implement these technologies. They need to be integrated into the Operational Technology (OT), Information Technology (IT), and management systems of the manufacturing organisations that wish to utilise these technologies. Figure 1, derived and expanded from [12], illustrates the complexities of implementing smart manufacturing systems. There are various interconnecting layers and systems, different types of devices and machinery, and legacy equipment and systems. The data and communication demands of this pyramid of technologies and entities could benefit from the improved capabilities that today's high-speed digital wireless communications could offer.

To maintain control of their factories, the stakeholders within smart manufacturing systems need access to tools and architectures that can aid the organisation and design of a complex CPPS. For example, the Smart InforMation PLatform and Ecosystem (SIMPLE), see Figure 2, is designed as scaffolding or a framework for smart manufacturing: "The SIMPLE platform development...objective is to stimulate the development of manufacturing-specific but cross-sector and cross-industry digital capabilities" [12]. The SIMPLE modular and software-driven architecture is reliant upon connectivity, not only in terms of the physical connections but how data is connected, translated and moved between entities. Physical communication, whether wired or wireless, is the conduit for data connectivity. The capabilities of 5G technologies adds more options to the design of smart manufacturing systems that implement SIMPLE or similar frameworks.

C. NEW RADIO TECHNOLOGIES, 5G AND WI-FI 6

The success of mass-market global telecommunications results from the collaboration of multiple organisations and stakeholders. Universally implemented technical standards have enabled the rapid growth and worldwide spread of cellu-

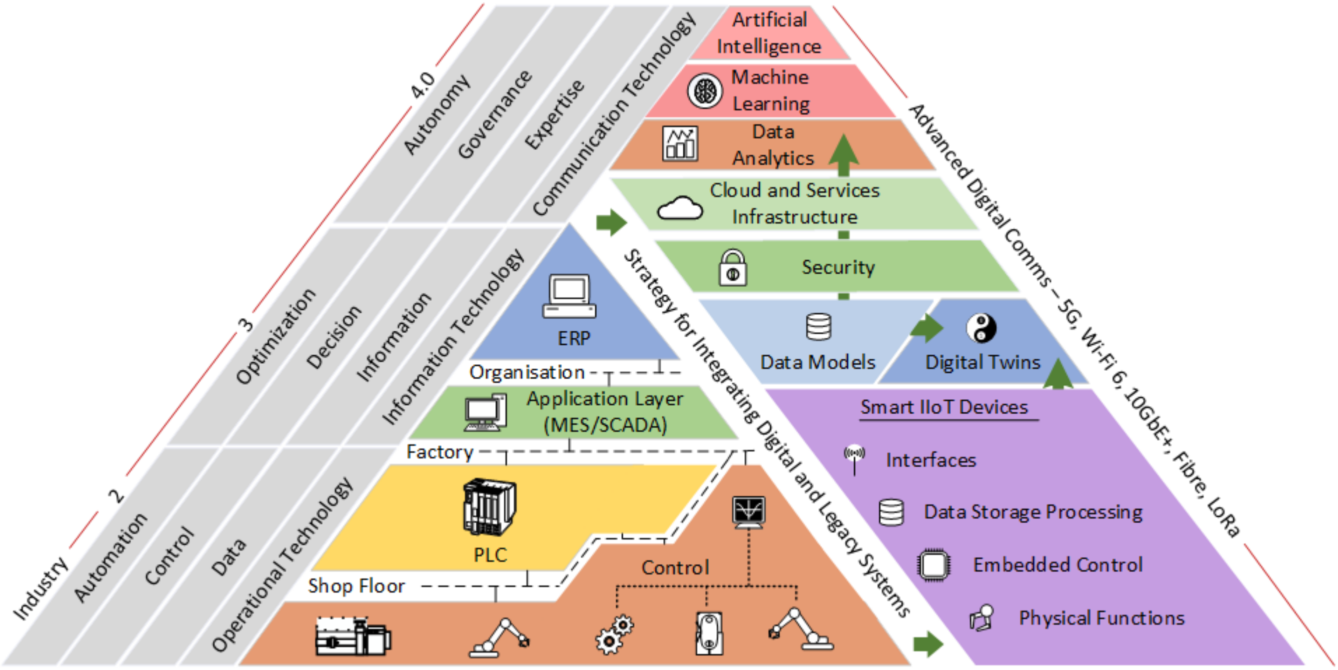

FIGURE 1. A pyramid of manufacturing technologies that illustrates the potential complexity within smart manufacturing systems [12]

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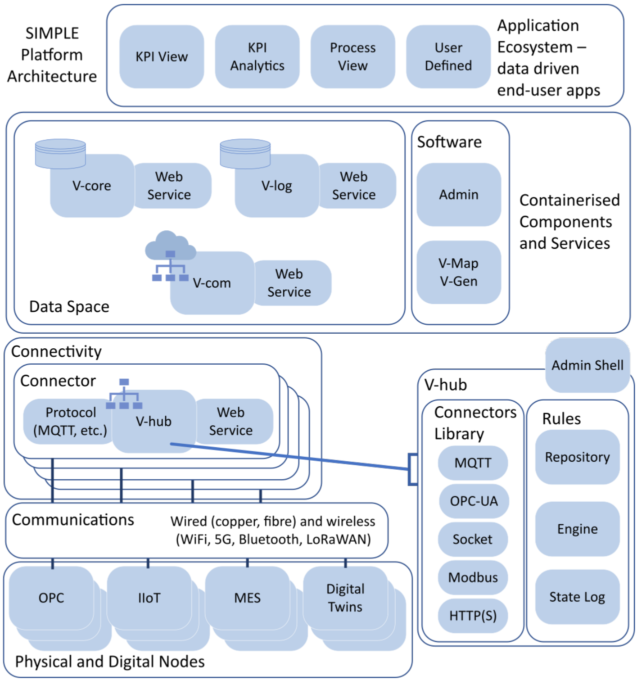


FIGURE 2. The SIMPLE framework to support smart manufacturing technologies, which is derived from [12].

lar communications. Each generation of telecommunications technology, Table 2, increases the capabilities of communications, which in turn drives demand for more bandwidth and features as new applications and use cases emerge. 5G is the newest release of cellular communications deployed. It is another step up in capabilities over the previous generations. This includes the introduction of features to enable additional use cases for International Mobile Telecommunications (IMT) as stated by the International Telecommunications Union (ITU) in 2015. These new usage scenarios were stated as [14]:

- Enhanced Mobile Broadband (eMBB) - This is targeted at the human use of multimedia content, services and data. A higher data capability drives the take-up of higher-density data services. Enhancing mobile broadband capability at high user density events (i.e., crowded locations) and improving data rates for roaming users. This is beneficial for the users, service providers and businesses that can use those services.
- Ultra-Reliable and Low Latency Communications (URLLC) - Improving data throughput, latency, and availability are beneficial for several domains that want to engineer new advanced systems, these domains include industry, medical systems, power grids, smart city automation, and transportation.
- Massive Machine Type Communications (mMTC) - Many multiples of devices are deployed to provide data, e.g., from sensor networks. These devices may be required to operate for many years on battery power. Applications can include remote monitoring of installations, building monitoring, providing agriculturally data, and smart cities.

Each of the generations of cellular communications has needed to support the older generations to enable the technology to transition over several years across the global mar-

TABLE 2. Fifth Generation New Radio (5G NR), simply known as 5G, is a recently deployed global release of mobile cellular communications

Generation of mobile communications (nG)	The primary decade of deployment and take up	Principle technologies used in cellular communications across the world
1G	1980s	Analogue transmission, Total Access Communication System (TACS), Advanced Mobile Phone System (AMPS), Nordic Mobile Telephony (NTC)
2G	1990s	Switch to digital transmission, support for Short Message Service (SMS), Global System for Mobile (GSM) became a dominant technology, Code Division Multiple Access (CDMA) was specified in Interim Standard 95 (IS-95), others included Digital AMPS (D-AMPS) and Personal Digital Cellular (PDC)
3G	2000s	Introduction of mobile data services, High Speed Packet Access (HSPA), Wideband Code Division Multiple Access (WCDMA) used in Universal Mobile Telecommunications System (UMTS), CDMA2000 (successor to 2G's CDMA)
4G	2010s	Long Term Evolution (LTE), and revisions, supporting packet switching on an IP network
5G	2020s	New Radio (NR) with frequencies up to 6GHz and at millimetre wave (mmWave) over 24GHz, supporting defined use cases are Enhanced Mobile Broadband (eMBB), Massive Machine Type Communication (mMTC) and Ultra-Reliable and Low-Latency Communication (URLLC)

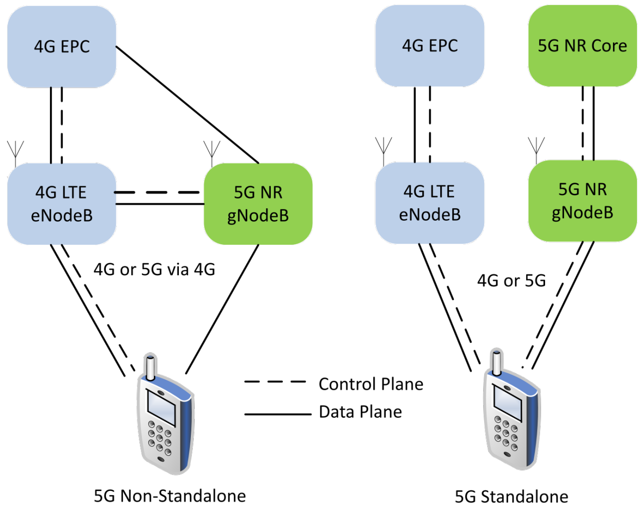


FIGURE 3. 5G Non-Standalone vs Standalone.

ket [15], [16]. This has resulted in two primary methods for a 5G device to connect to a 5G network. A 5G device, in the United States and China, will initiate a connection directly with a 5G base station. This is called *standalone* or *SA*. In the rest of the world, including Europe, a 5G device will initiate a connection with a 4G base station and then be passed to the 5G network. This is called *non-standalone* or *NSA* [17]. See Figure 3. In both cases, if no 5G network is available then 4G or lower is used. Devices that are programmed to operate in only NSA mode may present a problem to private 5G networks that only deploy 5G only base stations. Overtime devices will need to be programmed to support standalone as 5G base station nodes and core networks become the most prevalent.

D. 5G IN MANUFACTURING

Manufacturing plants typically consist of several fixed machines connected via wired Ethernet networks. The introduction of new technologies to the manufacturing space has highlighted a requirement for reliable wireless communication in industrial environments. AMRs (Autonomous Mobile Robots), augmented reality and virtual reality are transforming manufacturing and IIoT projects are driving an increasing demand for sensor data, sometimes in locations that do not lend themselves to being wired. Note, the term AMR covers all forms of mobile robots, including wheeled, e.g. AGVs, and legged systems, e.g. the infamous Boston Dynamics Spot "dog" robot.

Typical enterprise Wi-Fi networks are vulnerable to changes in the number of connections and the quantity of data being exchanged. Wi-Fi-based components will employ strategies to limit the load on the network. An AMR will use onboard maps, missions, and obstacle avoidance routines, requiring a minimal exchange of commands and status data over Wi-Fi to complete a task. Video-based devices may employ compression/decompression routines that introduce additional processing time.

5G offers the potential to expand the capabilities of these technologies and present new opportunities and potential use cases for flexible connected manufacturing. Features such as dedicated channels and the lower latency promised in the specification should lead to more deterministic communications, allowing for some aspects of control to be handled on the edge. The network can also be private, dedicated to a particular site, which would allow the mix of channels and features to be tailored to the company's requirements.

This work has looked at some of the use cases for advanced wireless communications, Table 3. The use cases have been placed under vision, IIoT, logistics, flexible manufacturing, and safety categories. The advantages of the use case to manufacturing are summarised, as are the advantages over a wired solution. The challenge of implementing the given use case on established Wi-Fi technology is summarised, and the advantages of using 5G are listed. The final column provides a suggestion of the kind of 5G equipment that would be required within the marketplace to realise the use case. At the time of this work, it was observed that there are a limited number of dedicated industrial devices with 5G built-in. The availability of manufacturing-specific 5G equipment is mainly concentrated on the provision of a router to send data collected by other equipment over a 5G network.

The availability of industrial equipment and sensors with

TABLE 3. Use cases for industrial 5G

Category	Use case	Use case advantages	Versus wired comms	Wi-Fi challenges	5G advantages	Realising 5G
Vision	Augmented Reality	Enhanced work instructions; machine status; visually guided maintenance	Freedom of movement in and around machines, indoors or outdoors	Slow network due to edge-based image processing data volumes, impacting other network traffic	High data rates; dedicated channels	5G headsets with built-in 5G or adapter and good uplink rates; engagement with AR hardware companies
	Virtual Reality	Virtual models inspection/testing; training away from the factory floor; training in controlled environments	Freedom of movement	Large amounts of video data slowing networks	Ditto	5G routers to replace existing wired and wireless connections
	Inspection	Powerful edge computing image analysis; remote inspection with mobile robots	Mobility; indoors or outdoors; elevated structures or equipment	Providing a high capacity and reliable edge connection	Ditto	5G routers to replace wired connections
IIoT	Predictive maintenance	Retrofit sensors, e.g., vibration or temperature; edge computing analytics	Greater freedom in sensor positioning with less disruption	Reliability	A large number and lower power sensor and compute nodes	Sensors development; engagement with sensor firms; solving power routing
Logistics	Enhanced AGV operations	Shared obstruction and traffic information for route optimisation	n/a	Channel connection limitations and latency, channel availability at transmission time	Dedicated connections, low latency	5G routers fitted to AGVs, software development
		Identifying obstructions	n/a	Ditto	Dedicated, high-capacity channels	5G routers, suitable cameras, and image recognition software are available
		Factory map or 3D plan updates	n/a	Ditto	Ditto	5G routers available; use of point clouds from laser scanners possible; software development
		Edge control of vehicles; flexibility with edge-controlled missions and course adjustments; edge-to-center coordination	n/a	Ditto	Dedicated connections; low latency	Low-cost 5G vehicles, control software for routing
	Coordinated delivery and shipping	Optimised and coordinated deliveries and collections via public 5G networks; real-time estimated arrivals; loading bay locations	n/a	Local router limits	Utilise widespread public networks; small data requirements can be achieved with 4G	5G router availability
Flexible manufacture	Flexible distributed control	Simpler and lower cost stations for flexibility, quick reconfiguration and enhancement; rapid product changes and demand matching; central or edge control; different controller code developed and tested via DTs or virtual commissioning	Increased flexibility to move, add, and change stations and their operation	A limited number of connections, connection latency, network availability at time of transmission	A large number of connections, low latency, dedicated communication channels	Currently available soft Programmable Logic Controllers (PLCs) or standard PLCs used as centralised controllers; 5G router availability; testing of automation protocols over 5G; engagement with end users on suitable processes
	Movable stations	Local control of general-purpose automated stations using wireless communications; coordinated centrally or at the edge; quick augmentation and rearrangement to meet demand or process changes; spare capacity hire	Improves flexibility to move stations	Ditto	A large number of connections; dedicated communication channels	5G routers available to replace wired connections; existing production planning software may need additional development
Safety	Define safe areas	Scanning for hazards; distinguishing between humans and mobile robots and their proximity to machines; data and image processing at the edge	Additional options in sensor positioning with less disruption	Connection latency could lead to timeouts and false trips or delayed cut-offs	Low latency with dedicated connections	Justifying investment vs wired systems; engagement with safety manufacturers; development of 5G enabled safety systems; approvals processes

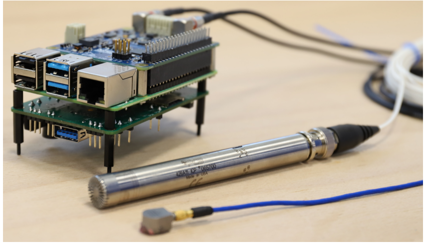


FIGURE 4. The Ventus 5G enabled industrial sensor (microphone and vibration pickup) developed at the Advanced Manufacturing Research Centre North West, image courtesy of The University of Sheffield.

built-in native 5G communications ability is required to aid 5G industrial take-up. An example of a 5G sensor is shown in Figure 4. It is in use at The University of Sheffield's Advance Manufacturing Centre North West. The sensor uses a microphone and vibration pickup to monitor the machining operation on a part. It sends data to a cloud compute server that can apply a Machine Learning (ML) model to fine-tune the machining speed. The machining speed adjustment caters for minute variations in the parts material and the cutting head to improve the quality of the machined surface. Whilst, ML can be run at the edge, more demanding ML may need cloud computation resources and the low latency communications provided by 5G.

Manufacturers will need to evaluate the benefits of using 5G in their factory networks against the additional costs of installing and running a 5G network. A 5G network installation will require specialist equipment and antennas. The equipment would require experts in mobile communication to install and configure and maintain it. An operating licence or subscription to a mobile operator is required. There is a need for manufacturers to gain or bring in 5G technical knowledge and for 5G equipment to become as straightforward to install as more familiar networking equipment. This issue may be particularly relevant when considering the needs of SMEs that may lack time and expertise in 5G technology.

The obvious competing technology for 5G in the factory is Wi-Fi, commonly seen in enterprise IT systems. The latest version of Wi-Fi is Wi-Fi 6 (IEEE 802.11ax) with an increment in capabilities over the previous standards (IEEE 802.11ac and IEEE 802.11n). Wi-Fi networks require a simpler installation. Once a Wi-Fi router has been purchased, most organisations would have all the expertise, necessary to install and maintain the network, in-house. This coupled with the improved performance of Wi-Fi 6 could challenge some use cases for 5G. One use of the 5G AGV testbed will be to test the limitations of 5G and Wi-Fi 6 technologies.

III. 5G AGV MANUFACTURING USE CASE

The choice of an AGV as a 5G platform supports several of the categories and use cases listed in Table 3. AGVs are traditionally used to aid in logistics, moving parts and goods around factories and onward to loading bays for final dispatch. AGVs, and AMRs in general, are being used in Flexible Manufacturing Systems (FMS), and in cobot applications to integrate automation into human-orientated manufacturing tasks. In Figure 5 a robot arm mounted on a MiR100 AGV is designed to support human operators in specialised manufacturing operations.

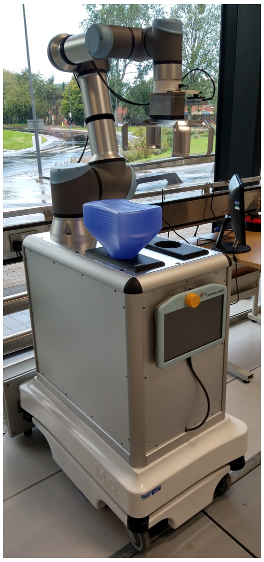


FIGURE 5. A robot arm on an AGV can be used as an automated aid for production and human operatives, i.e., as a cobot.

A 5G AGV will support safety and surveying operations, autonomously monitoring factory spaces for hazards and supporting factory operations. As new use cases for manufacturing DTs emerge a variety of methods to keep the data within DTs updated and accurate will be required. AGVs and AMRs as autonomous surveying systems are one of those methods. Furthermore, surveying functionality is useful for wireless site surveys to help determine potential sources of RF interference within factories.

A. EXAMPLES OF DEPLOYED 5G-ENABLED AGVS

The argument for deploying 5G within factories has been provided for several years [18]. A summary of AGVs and AMRs and their relation to 5G and relevant applications can be found in [9], though it finds only one realised AGV, a robot lawnmower teleoperated over a 5G connection utilising Huawei equipment [19]. An AGV is controlled over 4G/5G Ericsson equipment in [20]. They choose a couple of Key Performance Indicators (KPIs), the guidance error and the current consumption. The argument provided is that a lower latency connection should provide improved control of positioning and less power consumed on course corrections. The 5G connection saw a 3.1mm average guidance correction and 2.78A average current consumption compared to 4.8mm and 2.47A over 4G. The 5G control improved guidance accuracy whilst reducing current consumption by 11%. They further showed that increased link latency and packet loss in a 5G link would increase the AGVs guidance error and hence its current consumption. This limited experiment does start to gather evidence for the advantages of 5G communications for use in smart factories.

In [21], a remotely located ML model is used to anticipate AGV guidance errors and provide corrective actions when a 5G link experiences perturbations. Wireless links can be subject to degradation and if the guidance of an AGV is not computed locally then such predictive methods could help maintain performance levels.

5G is chosen as the communications link in [22] because of its performance advantage over 4G and Wi-Fi. In that work, two AGVs communicate over 5G to enable the transport of a large load. The 5G link enables one AGV to track the movement of another AGV with a small margin of error, enabling the conveying of a shared load. This demonstration of AGV cooperation shows the value of low-latency wireless communication links. A similar leader-follower configuration of AGVs is presented in [23], where a Kalman filter is used to reduce the control delay in the 5G link to improve the tracking accuracy of the following AGV. Indeed, time-sensitive applications are a reason to choose a 5G link over earlier wireless technologies.

Ensuring a consistent Quality of Service (QoS) in an environment where 5G is deployed is the focus of [24]. They argue that factories and logistics environments change over time and those changes can impact the quality of the wireless connections and the required configuration of equipment. An AGV is used to monitor communications KPIs in a 10,000m^2 area. The AGV is seen as an efficient solution compared to human walking surveys. The data collected is relayed to an aggregating KPI analysis dashboard. The solution is stated as providing cost savings between 30% to 70% compared to previous testing regimes. The use of an AGV, AMR, or drone for automating signal surveys to aid the determination of antenna locations and wireless equipment parameter configuration makes sense, particularly for larger industrial installations. Our own research on 5G NR signal characteristics within industrial environments [25] confirms that the theoretical maximum settings for configuration parameters will vary, hence the need for easy-to-perform wireless site surveys within industrial spaces.

These examples of 5G-enabled AGVs have been built for a specific experimental purpose. The authors' AGV platform is designed to support our research on the smart manufacturing use cases listed in Table 3. Further, it will interface with other manufacturing cells within WMG's industrial laboratories.

B. THE WMG 5G AGV TESTBED

To evaluate the use of 5G within industrial applications and provide a platform to trial the benefits, and challenges, of using 5G communications in smart manufacturing use cases, particularly for SMEs, a testbed has been created. The testbed chosen combines an industrial AGV with a 5G router. The AGV is from Mobile Industrial Robots (MiR), their MiR100 AGV provides a mobile platform for industrial applications and logistics, see Figure 6. The standard communications of the MiR100 is via traditional Wi-Fi (IEEE 802.11a/n/g/ac).

FIGURE 6. An industrial mobile guided platform vehicle is used in the 5G test case (image courtesy of Mobile Industrial Robots).

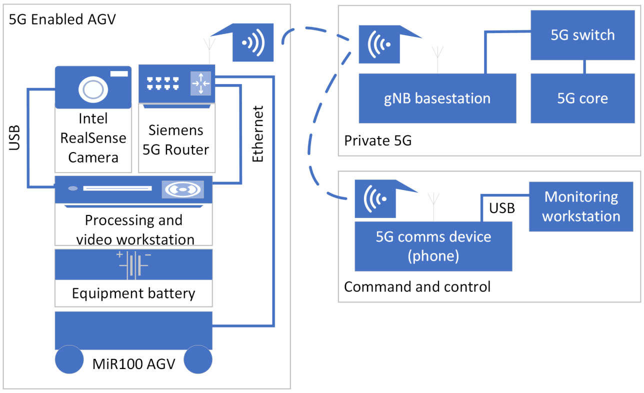


FIGURE 7. Overview of the 5G-enabled guided vehicle.

The 5G router increases the communications capabilities of the AGV. The addition of 5G provides the ability to support high-density data applications, e.g., high-resolution digital video without the need to share the Wi-Fi network with other office and factory devices. This has advantages for both the AGV and the Wi-Fi network. For the AGV, it enables improved communications bandwidth and latency. Improved latency is beneficial for applications that include teleoperation and remote feedback control. The benefit for the office/factory network is it enables the network to function without the bandwidth being consumed by high data volume smart manufacturing applications. This can contribute to the resilience of operations. Running the factory systems on separated communications channels can contribute to performance and security goals (discussed further in Section IV-A).

A schematic of the 5G AGV is shown in Figure 7. An equipment battery is used to supplement the AGV's drive-train battery, enabling the AGV to operate for longer. An Intel RealSense digital camera, incorporating Light Detection and Ranging (LiDAR) is linked to a video processing workstation via a Universal Serial Bus (USB) connection. The processing computer runs LiDAR software. The 5G router is linked to the AGV and the computer workstation over Ethernet via a pass-through gateway. The AGV is configurable with a Siemens SCALANCE MUM856-1 industrial 5G router or a Netgear 5G router. Testing a variety of different router makes is one of the testbed's uses.

The 5G router connects via a SA 5G connection to a Generalised Node Base (gNB) base station. The gNB links via a 5G switch to the 5G core providing a 5G SA private network. The private network is licensed by the British regulator the

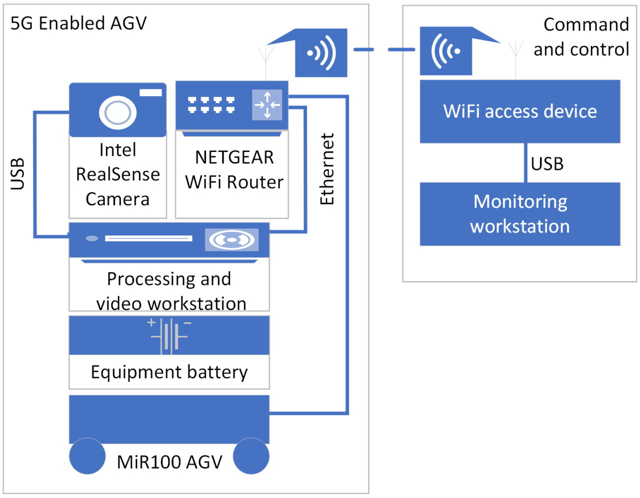


FIGURE 8. Overview of the Wi-Fi-enabled guided vehicle.

Office of Communications (Ofcom). The AGV's 5G router exposes the web interface to the private 5G network and port forwarding is used to expose the workstation.

The command and control (C&C) monitoring workstation for the AGV testbed connects to the same 5G private network. The connection is through a 5G SA mobile phone that is acting as a 5G modem. This modem is connected to the C&C workstation via USB. The C&C workstation provides Mobile Edge Computing (MEC), a.k.a. Multi-access Edge Computing capability. The MEC functionality allows for a connection to the AGV's exposed web interface, via a ROS (Robotic Operating system) bridge. Furthermore, there is the ability to remote desktop onto the AGV and to access the LiDAR streaming port.

The 5G AGV can be used for Wi-Fi communications applications and Wi-Fi testing. A schematic of the AGV in the Wi-Fi configuration is shown in Figure 8. The configuration is similar to the 5G configuration with the same software, however, Wi-Fi routers are used instead of 5G routers and modems. Then the AGV connects via Wi-Fi to an access point (AP). The C&C workstation for the AGV connects to the AP via USB. Figure 9 shows a picture of the completed AGV in use.

C. 5G AND WI-FI 6/6E CONSIDERATIONS FOR SMES

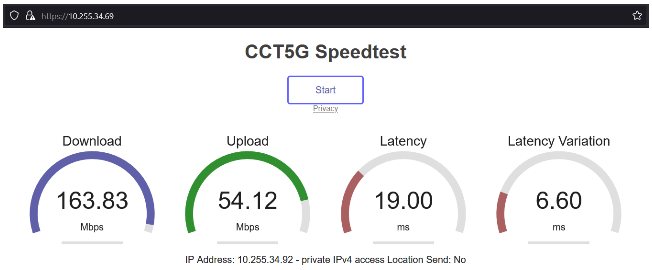
Manufacturing SMEs needing to implement smart manufacturing use cases will require advanced wireless communications (see Table 3). They would consider deploying Wi-Fi since organisations have experience with Wi-Fi from their IT operations. However, 5G communication is seen as an important technology for industrial economies [26]. SMEs will need assistance in determining whether 5G or Wi-Fi 6/6E, or both, will meet their requirement.

Note that our 5G configured AGV system has the additional equipment that is associated with the 5G private network, and that this additional equipment sits between the AGV and the C&C workstation. This means the 5G communications path has extra steps compared to the Wi-Fi path. Despite this added complexity, the 5G communications performance is considered superior to the Wi-Fi performance when correctly configured and managed, particularly under heavy use, where QoS becomes important. QoS is critical for manufacturing applications. The higher 5G performance compared to Wi-Fi is due to the different nature of their design:

FIGURE 9. The completed 5G MiR100 AGV carrying a sub-assembly.

- Wi-Fi uses Carrier Sensing Multiple Access with Collision Avoidance. Each wireless node in the system will listen for idle radio transmissions before sending. The transmitting node will send a *Request to Send* message and wait for a *Clear to Send* message before transmission. Not having the ability to sense the channel while transmitting results in inefficiency [27].
- In cellular communications time slots are allocated on the downlink and uplink and assigned to nodes as and when they are needed over a fixed period, although there is some wastage in the system collisions are generally avoided.
- Wi-Fi has the Control Plane inside the Data Plane, whilst 5G (and 4G) have a separate Control Plane and Data Plane.
- Wi-Fi's unlicensed spectrum may result in access contention issues from unneeded devices if the Wi-Fi network is not correctly configured and managed.

It can be considered that 5G is a proactive approach [28] to handling message transmission and Wi-Fi is a reactive approach. Wi-Fi has a bandwidth drop when the probability of collision is high [29]. This means that for large numbers of nodes, high data bandwidth, and low latency applications 5G communications will provide the required performance for future flexible manufacturing applications [9]. It was shown in [30] that Wi-Fi 6 can outperform 5G in certain situations where the distance to the antenna is short, whilst



IP Address: 10.255.34.92 - private IPv4 access Location Send: No

FIGURE 10. 5G AGV link performance.

5G's performance can hold up as distance increases. Further, they state that achieving theoretical maximum data throughputs is unlikely, which our tests in industrial environments show [25]. Additional evidence is required to support all of these claims, and our 5G AGV testbed will support the experimentation required to build up the evidence knowledge base and provide the industrial benchmarks that have been stated as lacking [31].

D. 5G AGV TESTBED IN OPERATION

Validating the performance of 5G within manufacturing is one aim of the research project. The 5G link performance for the AGV testbed is shown in Figure 10. The link is providing a download/upload of 163/54 Mbps with a latency of 19±6.6 ms. When testing the streaming of video from the AGV it is providing no noticeable lag when compared to the lab's existing Wi-Fi which does demonstrate lag under the same streaming conditions. One aspect of the link performance of interest for manufacturing applications is the latency figure. Latency is affected by several hardware and software factors, having a reliable low-latency connection with a target in the single-digit millisecond range aids the implementation of time-sensitive applications. This was a reason 5G was chosen for the wireless link in some of the AGV research discussed in Section III-A.

Another application of the 5G AGV testbed is to test AGV teleoperation over wide area networks. An operator located in Hamburg, Germany, was able to use the AGV located in a laboratory on the University of Warwick campus in England. Usage included negotiating obstacles within the laboratory. The AGV control link was over public 4G/5G cellular networks with the final hop over the testbed's 5G private network for a total distance of 1109 kilometres.

These types of high bandwidth and low latency applications and reasons to deploy faster wireless infrastructure. An automated assembly manufacturing cell may not generate large amounts of data. Figure 11 shows a plot of the amount of configuration and monitoring data to/from a production cell. The Open Platform Communications Unified Architecture (OPC UA) format is used to exchange data between the monitoring and configuration server and the cell. During the normal operational phases of the cell, the data packets are a few hundred bytes or between 3000 and 4000 bytes in size, with a few peaks higher during initiation phases.

Furthermore, the rate of the data packets is modest. Figure 12 is displaying mainly 10 or 40 packets per second, again with a few higher peaks at phase transitions. This shows that SMEs do not need 5G communications as a replacement for hardwired existing functional systems. SMEs can assess 5G for when they want to add new features (see Table 3) to their manufacturing processes.

IV. 5G FOR RESILIENT FUTURE FACTORIES

During this research, it has been noted that the use of 5G within factories for smart manufacturing applications is in its infancy. 5G's specific goals for the URLLC and mMTC use cases will require readily available hardware and supporting software, and the knowledge to implement 5G within industrial locations. The above 5G AGV testbed is designed to accelerate the knowledge of practical 5G applications. Furthermore, the research has found other considerations around the challenges in the move to digital manufacturing.

A. 5G AGV TESTBED USE CASES

In addition to supporting some of the industrial use cases listed in Table 3, the 5G AGV provides an adaptable platform for use as a testbed for advanced industrial wireless communications in a variety of manufacturing and logistic situations. The use cases include:

- as a research tool and 5G demonstrator within factory settings;
- for testing the transmission of high-definition video and other high-density data over 5G and Wi-Fi within a factory application;
- for performance testing of advanced wireless communications and communications equipment targeted at manufacturing applications in an industrial environment;
- testing autonomous 5G and RF surveying techniques in industrial spaces;
- as a platform to test cloud versus mobile edge processing in manufacturing CPSs;
- to investigate cybersecurity issues and mitigation techniques in manufacturing CPSs;
- the platform's private 5G network is used for the testing of 5G's designed-in usage scenarios (see Section II-C);
- to analyse the beneficial claims for 5G within factory locations;
- to research new uses of AGVs and AMRs in factory spaces;
- testing the interaction of AGVs and AMRs with FMS cells and cobot operations (Figure 13 shows the 5G AGV delivering an assembly to a robot station).

Several facets contribute to the overall performance of end-to-end communications within 5G systems. As stated in the list above, one of the goals of the industrial 5G AGV testbed is to research the performance of 5G within industrial settings. Knowledge of 5G performance factors within industrial spaces will be beneficial to industrial systems designers and automation engineers. The factors for research include:

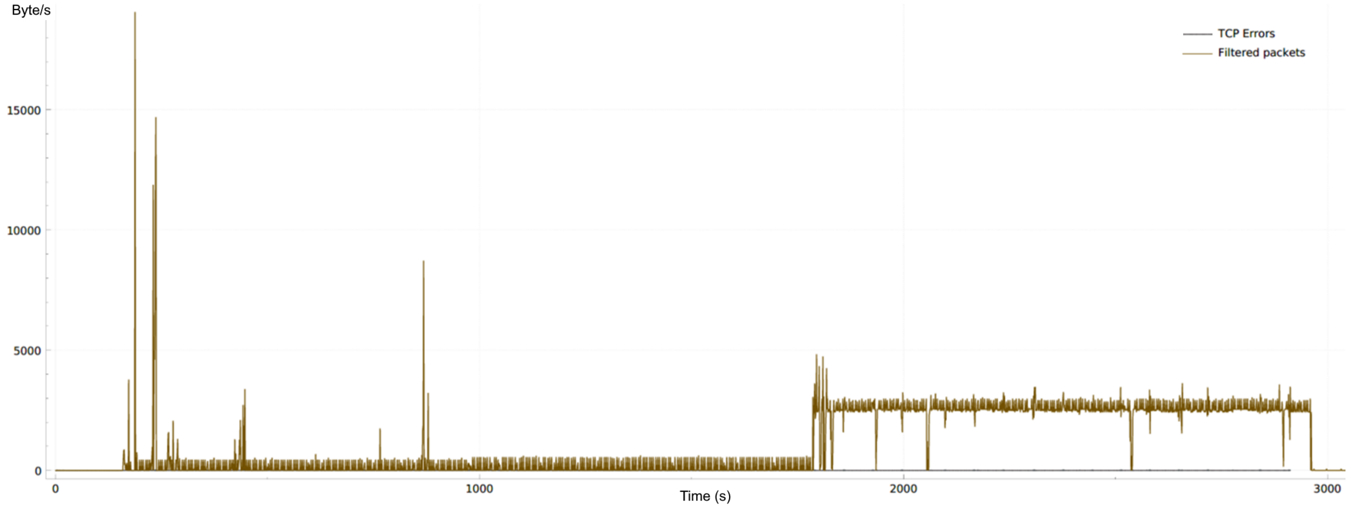


FIGURE 11. OPC UA data size in a manufacturing cell.

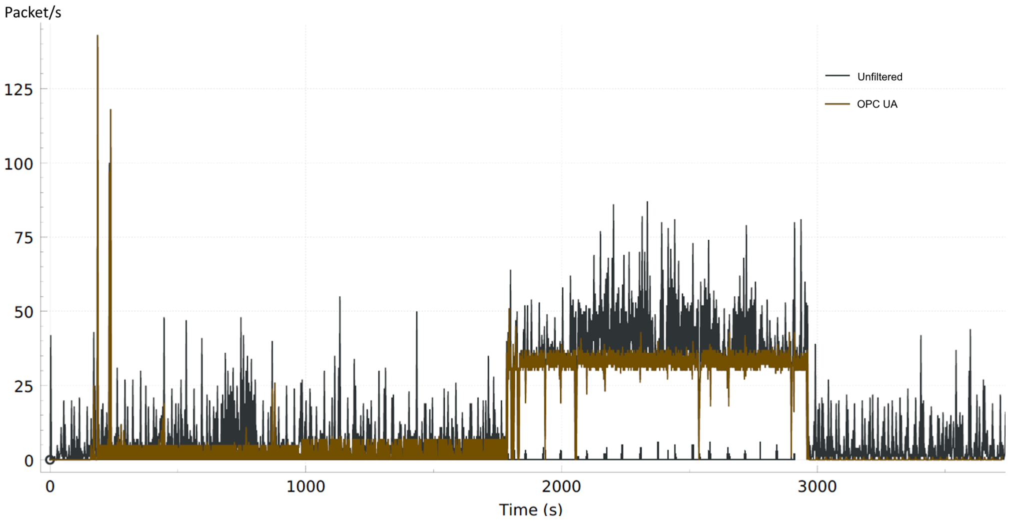


FIGURE 12. OPC UA data packet density.

FIGURE 13. 5G AGV delivering an assembly to a robotic FMS station.

- the capability of data processing and sensor systems, including the performance of the processor, system memory considerations, and network card or interface performance;
- data channel issues, including the number of acceptable corrupt packets, packet overflow, packet underflow, packet checksums, and packet latency;
- RF issues related to the position of equipment and multi-path reflections;
- the systems required to instrument, monitor and provide reports on the wireless communication channels;
- separation of communications between OT and IT for operational and cybersecurity considerations.

The design and implementation of factory 5G communications systems must consider the day-to-day operation and ongoing maintenance. Just as wired networks are monitored for issues, wireless "situational awareness" is important. This is done through the extension of existing network and plant monitoring systems to include support for advanced wireless communications, alternatively, the implementation of separate monitoring dashboards with the ability to feed into existing systems if necessary, as with WMG's OPC UA server dashboards. Physical security and cybersecurity are additional considerations.

The physical security of communications hardware is likely to fall under the security policies of other plant and factory systems. The wireless communications equipment will require protection from physical tampering and potential vandalism. This requires consideration of equipment position, physical protection mechanisms, and access control policies.

Cybersecurity and the split between OT and IT systems, and their sub-systems, have system design implications. Separation of communications channels is a likely requirement to support cybersecurity and system design goals. There is a variety of ways to achieve separate communication channels. Separate physical hardware is one option. Another option is to have virtual communications channels on an existing network, using network virtualisation or a virtual private network. 5G uses network slicing to separate applications. Operations can dedicate a slice of the spectrum and network services to applications to guarantee QoS requirements.

In the design and maintenance phases management of the communications system assets is a consideration. For large installations, there are potentially hundreds or thousands of individual pieces of communication equipment. The unique International Mobile Subscriber Identity (IMSI) number for the endpoints will require management systems, along with the associated Subscriber Identity Module (SIM) cards, or the "embedded" or "electronic" version (eSIM). The requirement for SIM programming or provision by a service or equipment supplier is a consideration. Industrial locations that require many endpoints may rely on system suppliers for SIM management. Security issues related to IMSI numbers and SIMs (the cloning and stealing of SIM cards) have been reported in the past, thus IMSI and SIM security is a consideration.

B. CHALLENGES WITHIN SMART MANUFACTURING

It could be argued that the implementation of advanced wireless communications within manufacturing facilities is another example of the industrial domain deploying new technology as it emerges. Manufacturers have often taken new technology and applied it to the shop floor to aid productivity. Technology advances allowed industrialists to develop the PLC, the production line robot, Computer-Aided Design (CAD), and Computer-Aided Manufacturing (CAM), through a host of emerging new digital manufacturing technologies (see the list in section II-B). However, manufacturers must take credit for accelerating or inventing advances in some technologies. 5G is an example as the design includes the capabilities to support the I4.0 vision. Yet in this rush to new digital manufacturing and advanced wireless communications technology, some often unconsidered challenges are present [12]. These challenges include:

- the increase in the heterogeneity of the systems, the number of system elements and the number of management points;
- the handling of the natural division between enterprise IT and factory OT;
- the potential plethora of different data formats and design models between system elements;
- obtaining good quality data from the new systems and sensors;
- the appropriate formatting and analysis of data;
- making data available, understandable, and useful;
- the integration and communication between disparate systems;
- the need for commonality in machine-to-machine communication and understanding;
- improving connectivity, which can be fragmented, between systems and sub-systems;
- the resilience to handle changes and absorb the impact of external events;
- the consideration and catering for cybersecurity;
- efficiently handling the lifecycle of this digital manufacturing super-system and the myriad of its elements.

The resources of multi-million or multi-billion pound industrial companies will allow them to address these challenges in the deployment of digital-based smart manufacturing and 5G technology. However, resource-limited SMEs may be looking at suppliers and other knowledge sources to address implementation challenges. This 5G AGV project is part of the process of building and disseminating relevant knowledge, particularly the role 5G can play in being an enabler in overcoming some of the challenges raised.

Other ways to build the requisite knowledge include the implementation of standards for I4.0 technologies. Standards can help alleviate some of the challenges, e.g., around data formatting and diverse system integration. The standards on I4.0 would be available to manufacturing system designers to help overcome any barriers to smart manufacturing implementation. Such I4.0 standards would build upon the existing well-established manufacturing technology standards long established through national and international trade bodies and standards organisations. This means standards are not always open and accessible, requiring membership of organisations or access via paywalls.

There is the Reference Architecture Model Industry 4.0 (RAMI4.0) [32] that came from the I4.0 vision. RAM4.0 is a conceptual standard that recognises the importance of a common description of all the manufacturing entities that can exist in a smart factory. However, it is adding another layer on top of the existing body of standards. Maybe it would have been more productive to build an open software tool to help engineers productively understand how to apply the existing standards to smart manufacturing designs, systematically addressing the complexity involved in such highly data-driven systems.

There is the potential for digital twinning techniques to aid the management of the complexity within large-scale smart manufacturing systems. DTs can ensure that changes to CPPSs can be made that are beneficial to the system throughout its life cycle [33]. To enable effective I4.0 systems and their DTs the supporting communication systems must be capable of handling the data loads, latency, and response times. This provides a case for 5G as it is designed to cater for these use cases. However, some manufacturers, possibly SMEs, may view 5G seen as too challenging for deploying an industrial wireless solution. This is when they may look to the familiarity of Wi-Fi, and the newer Wi-Fi 6 capabilities to provide the communication link. Wi-Fi 6 boosts the performance of the long-established Wi-Fi technology, but similarly to 5G, the complete abilities of Wi-Fi 6 within an industrial setting need to be fully understood.

C. ASPECTS OF MANUFACTURING RESILIENCE

The manufacturing sector was affected by global events from 2019 onward that have reawakened interest in industrial resilience [34]. Events that tested industrial resilience included the coronavirus pandemic, the Suez Canal blockage, a semiconductors shortage, cyber-attacks, and political upheaval. Industrial resilience can be examined at three levels, from the national or *macro* level to the local or *meso* [35] level, and down to the factory or *micro* level, see Table 4.

Resilience at the macro level is often associated with ensuring the continued operation of Critical National Infrastructure (CNI) and other societal systems. This is driven by government policies and national and international organisations. Protection of CNI and similar critically required systems is guided by Resilience Engineering (RE) [36]. Resilience at the meso level is associated with regional policies and local systems, influenced by both the macro issues and the lowest level micro issues. It is at the micro resilience level that factories, organisations, and individuals have the most direct influence on resilience factors.

At the micro level resilience is often addressed under the guise of Business Continuity Management Systems (BCMS), and operational procedures and processes which include monitoring, testing, maintenance (including predictive maintenance), the use of KPIs, health and safety procedures, physical site security, and cybersecurity. Therefore, organisations may not be consciously performing RE, but they are aware of potential threats to day-to-day operations. However, RE looks beyond day-to-day operations to enable systems to handle more extreme unexpected disruptions and threats, see Table 5.

Smart manufacturing technologies are used to improve production efficiency, reduce costs and improve productivity. If the deployment of digital factory technology is further aimed at increasing system resilience, a desirable trait, then engineers should incorporate aspects of resilience within system designs. However, this requires them to understand the concept of resilience and how systems can contribute to it. RE at the micro level is not yet widely studied with operations focused around a BCMS for day-to-day risk management. Furthermore, risks and resilience aspects are mainly addressed qualitatively.

The 5G AGV platform aims to use the data it generates to investigate quantitative methods of measuring system resilience, particularly around the role advanced wireless communications have to play in improving manufacturing systems resilience. The study of resilience for the test platform is likely to be concerned with micro-level issues. Yet, meso-level issues are of interest to the sector. For example, the availability of supply chain data to anticipate potential disruptions and therefore production delays, triggering the automatic reassessment of production scheduling and its impact on machine utilisation.

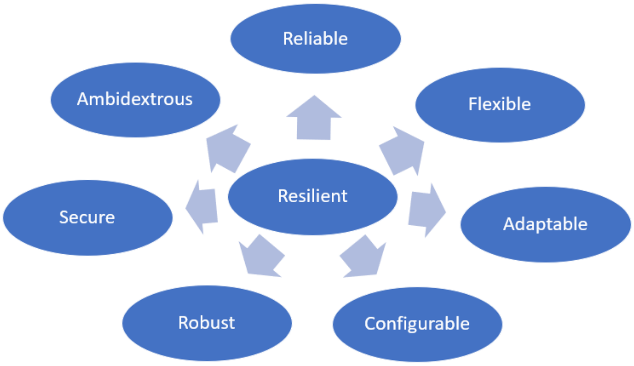


FIGURE 14. Desired system traits that contribute to resilience [34].

Improving the granularity of supply chain data is one vision for 5G's usefulness to manufacturing. The study of supply chain resilience [37] builds upon many years of study into *green supply chains* [38], [39] and forms part of manufacturers' sustainability aims. Alongside green and resilient the *lean* and *agile* paradigms have been used to study supply chains [40]. These various paradigms combine to produce Lean, Agile, Resilient, and Green (LARG) research [41], [42]. Achieving LARG goals requires timely data distributed over fast and efficient communication networks linked to sensor systems, i.e., the requirements of the I4.0 vision [43].

Engineers that do address resilience will find that it is multi-faceted and is achieved by ensuring systems possess several traits [34], see Figure 14. A system design or organisation taking steps to achieve several of these traits will raise the level of resilience. However, whilst using technology to implement these traits, technology could detract from resilience traits if it is misconceived or incorrectly designed and deployed. Section IV touched upon some of the overlooked challenges associated with introducing smart manufacturing technologies. For example, introducing new digital technology to improve a factory's adaptability and flexibility could detract from reliability and security due to increases in system complexity. System designers aware of these possible trade-offs can mitigate against them in their system designs.

The combined effort of engineers implementing resilience at the micro level will contribute to industrial resilience at the meso and macro levels. Similarly, policies and initiatives at the meso and macro levels will affect individual organisations and factories. An increase in the overall industrial resilience of an economy is seen as a beneficial goal for nations and

TABLE 4. Macro, Meso, and Micro resilience levels, from [34]

Level	Coverage	Applicability	Examples
Macro	National and multinational	Governments and large organisations with considerations covering critical infrastructure over multiple sites	Networks of power, communications and transportation, supply chains and logistics, social structures, law and order, health systems, financial systems, labour markets
Meso	Limited geographical areas and buildings	Local facilities and branches of organisations, medium and small enterprises	Business and industrial parks, factories and offices, public facilities and spaces
Micro	Building internals and worker groups	Internal systems and subsystems, operational systems, individuals	Plant and machinery, equipment, processes and procedures

TABLE 5. Disruptors impacting an organisation's resilience, from [34]

Level	Disruptors
Macro	Natural disasters (e.g., volcanoes or earthquakes)
	Disease outbreak (epidemic or pandemic)
	Extreme or severe weather events
	Market forces and new startups
	Changes in laws, regulations, and standards
	Changes in societal behaviour
	Technology obsolescence
Meso	Local power outage
	Animal or insect plagues
	Riots, protests and activism
	Trade unionism or strike action
	Raw material and parts shortages
Micro	Malfunctions
	Equipment fires
	Security breaches (e.g. theft or burglary)
	Deviation from procedures
	Cyber-attack
	Disgruntled, badly behaved, or ill employee

aids the related objectives of environmental sustainability and human well-being [8], [44].

D. 5G AS A FUTURE RESILIENCE AID

The 5G AGV testbed will be used to research the subject of resilience within smart manufacturing systems. In particular, how cellular 5G can be deployed to increase the various resilience traits, building upon the general aim to research 5G's use in building more capable and flexible manufacturing systems. Indeed, 5G will have a role to play in addressing some of the challenges described in Section IV-B, particularly around its ability to improve connectivity options, aid mobility and wireless options for equipment, improve communication latency compared to older wireless technology, and improve wireless data bandwidth. Future examples of 5G communications and other smart manufacturing technologies aiding improvements in system resilience include:

- for some manufacturing scenarios, improvements in system flexibility, with equipment and manufacturing cells supporting more than one task and being able to relocate automatically between workstations or production lines;
- improved worker flexibility, for example, workers supporting operations from home or for more than one site from a single location;
- reduction in reliance on human operators for equipment and the associated cost savings, e.g., internal factory logistics using autonomous vehicles to move parts reducing the number of required forklift operators;
- anticipation of materials and parts supply issues across a supply chain and using the data to enable diversion and re-balancing of the supply chain;
- the monitoring of human shop floor activity, work, and assembly to identify mistakes earlier requires improved communications to handle the vision and AI systems data and response demands;
- improving data collection, analysis, and at-the-edge analysis to get an increase in the granular detail on how a factory is functioning and using resources to aid in spotting areas for productivity improvements and cost reductions;
- keeping DTs updated and relevant in real-time to provide management with improved operational data and forecasts, and to support the ability to run multiple what-if scenarios.

The 5G AGV use case developed in this work will enable further research in 5G-connected AGVs in the following areas:

- single and group AGV intelligence;
- AI (machine learning) augmented AGVs to enable smarter AGVs beyond autonomous logistics and make the AGV part of a mobile and safe cobotic system;
- group intelligence and AGV sensing for dynamic and efficient routing in complex operations;
- centralised control and overview of large fleets of AGVs;
- inter-AGV communication via the 5G network for co-operative operations;
- and teleoperation of AGVs;

The use of smart manufacturing technologies, 5G communications, and the 5G-enabled AGV can aid the addition of the various resilience traits, shown in Figure 14, to a factory production process. However, as stated earlier, the challenge is not to assume the application of smart technologies will automatically improve resilience. Instead, systems designers, who are aware of the concept of resilience, are proactive in considering which traits can be improved without a negative overall impact. For example, a mobile cobot may be useful to support more than one process or workstation, but it needs to be robust enough to support multiple scenarios. If utilisation is not correct, one location could be starved of the cobot's time, detracting from overall efficiency and resilience.

The application of 5G within factories will enable and require new monitoring systems. The production process

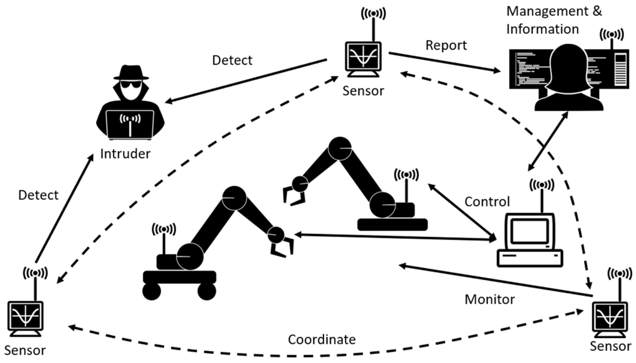


FIGURE 15. Using sensors to derive additional value from manufacturing data. Collecting additional data beyond traditional production figures can lead to new manufacturing insights, address threat and sustainability issues and improve overall resilience.

FIGURE 16. The 5G AGV testbed is operational and is being extended to other types of industrial mobile robots and manufacturing cells.

relies on KPIs to ensure manufacturing output and quality is being maintained. The world of smart manufacturing will be adding new monitoring points, KPIs, additional cybersecurity requirements, and further interactions between IT, OT, and supply chain systems. Sustainability and green agenda goals are likely to see research and investment in granular monitoring of power consumption, material, and parts usage, see Figure 15. 5G communications and sensors will be playing their parts in providing data to industrial information management systems. The mobility and cybersecurity use cases for enhanced monitoring are likely to see initial deployments.

One area that the research platform is targeted to improve is the dissemination of knowledge. 5G and all new smart manufacturing technologies will need to be understood by future automation engineers, system designers, and factory technicians. The requisite skills have been highlighted as a barrier to smart manufacturing adoption [45]. Education and training on digital manufacturing technologies will be a requirement for all types of industries. The 5G AGV will be a learning platform for advanced industrial communication technologies and future 5G-based smart manufacturing solutions. Furthermore, new technology should be intuitive to use and if complexity is evident in implementing 5G manufacturing solutions it will be highlighted.

V. CONCLUSION

The UK Government sees 5G as a key contributor to a modern economy, stating: "Our evidence is clear that the most significant economic benefits from 5G will come from widespread adoption of advanced 5G by industrial sectors, including manufacturing and logistics, and by public services." [26]. The incentive for this research was, and is, to enable SMEs to benefit from this vision.

The authors' aim was to implement a manufacturing-based system that can be used to perform a variety of tasks with 5G (and Wi-Fi 6) as the communications technology. It will allow SMEs, who may lack the resources to experiment with 5G communications, to see how 5G could be applied within their organisations. It has been achieved by augmenting an AGV with advanced wireless capability as a flexible and reusable testbed for mobile and adaptable manufacturing systems. The testbed is in use within WMG's industrial laboratories, see Figure 16, and the 5G communications can be applied to other types of AMRs, e.g., WMG's walking robot.

The testbed is being used to research the application of 5G's designed-in capabilities (URLLC, mMTC) to industrial environments and factory laboratories, i.e., not simply as a replacement for wired Ethernet connections, or the commonly used Wi-Fi. Existing networking technologies (wired or wireless) provide sufficient bandwidth for typical monitoring and configuration requirements. It will be new use cases, see Table 3, that will benefit from advances in wireless communications provided by 5G and Wi-Fi 6E.

Whilst we have seen examples of 5G AGV experiments that required low latency capability (see Section III-A), there is a lack of time-sensitive applications in the industrial 5G space. This was noted in [46], where they identified the need for more time-sensitive networking applications utilising 5G as a data link. This provides another research opportunity for the testbed. Furthermore, the research will investigate in detail 5G performance and RF issues in industrial locations, including additional performance comparisons between 5G and the latest versions of Wi-Fi (6/6E and the upcoming Wi-Fi 7).

Advanced wireless communication is only part of the overall picture of the digital technologies that are and will be part of the future factory, see Figure 1. The testbed will aid WMG and SMEs understand if 5G and advanced Wi-Fi will meet the claims made for them for many of the I4.0 visions. However, the authors found new smart manufacturing technologies come with challenges that may be overlooked in the literature and that need consideration. The discussion of those challenges in this work was to raise their awareness and ensure automation designers consider those aspects.

Manufacturing technologies are no longer viewed in terms of only internal factory systems. There are issues outside of the day-to-day factory operation that needs awareness, not only to ensure the resilience of operations but to satisfy wider society's resilience. A simple example on sustainability was noted in Section III-A, where a finer control of an AGV can reduce power requirements. Another example can be provided by the development of our testbed, which experienced delays due to issues with supply chains. How 5G can be used to gain insights into supply chains is another relevant area in research. SMEs using the 5G testbed to address smart manufacturing challenges will contribute to the operation of resilient future factories.

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DANIEL S. FOWLER has a B.Eng. (Hons.) in computer and control system engineering, an M.S. in forensic computing, and a Ph.D. in automotive cybersecurity, all degrees from Coventry University, UK. He is a Research Fellow in the Secure Cyber Systems Research Group at WMG in the field of secure and resilient system design. He has aided the engineering and delivery of several Innovate UK-funded projects. He contributes to the open source community through software and has written over 300 articles. He is a Chartered Engineer, and a member of the IET and ACM.

YUEN KWAN MO has a Ph.D. in communications and network engineering from The University of Warwick, Coventry, UK. He is a Project Engineer with the Connectivity and Communications Technology Research Group, WMG, The University of Warwick. His specialisms include: 5G and cellular communications for Industry 4.0, connected and autonomous vehicles, millimeter-wave communications, massive MIMO, precoding techniques and optimization algorithms.

ALEX EVANS joined WMG as a Project Engineer in 2017 and is now a Lead Engineer. During this time he has helped to deliver a number of industry collaborative advanced technology automation, digital manufacturing and data collection projects. Having received a BSc in Cybernetics and Control Engineering from the University of Reading in 1993, the early years of his career were spent designing, building and programming embedded microcontroller projects for a variety of customers in scientific and automation industries. A further 10+ years working for a leading HMI manufacturer and 9 years as a self-employed HMI and PLC software engineer enabled him to gain experience with all the leading PLC technologies, across a variety of sectors including automotive, textiles, food, utilities, building automation and energy monitoring.

SON DINH-VAN received a B.S. degree from Hanoi University of Science and Technology, Vietnam, in 2013, the M.S. degree from Soongsil University, Seoul, South Korea, in 2015, and the Ph.D. degree from Queen's University of Belfast, Belfast, UK, in 2019, all in electrical engineering. He is currently a Research Fellow with the Connectivity and Communications Technology Research Group, WMG, The University of Warwick, UK. He was a Data Scientist with Frequenz Gmbh, Germany, and a Visiting Researcher with Middlesex University, London, UK, in 2020 and 2021. His current research interests include 5G-and-beyond communications for manufacturing, wireless security, millimeter-wave, and machine learning.

BILAL AHMAD (Senior Member, IEEE) received the M.Sc. degree in mechatronics and the Ph.D. degree in automation systems from Loughborough University, Loughborough, UK, in 2007 and 2014, respectively. He was a Research Fellow and a Senior Research Fellow with WMG, The University of Warwick, Coventry, UK, and a Research Associate at the Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University. He is currently an Associate Professor with the WMG, The University of Warwick. He has worked on a range of high-profile national and international research projects. He is named as PI and Co-I on a number of Innovate UK and HVM Catapult projects. He has published his research findings in over 50 peer-reviewed journal articles and conference papers. His research interests are in the areas of manufacturing digitalization and lifecycle engineering of cyber–physical production systems, especially focusing on the design and deployment of real-time control systems and their connectivity with IT systems.

MATTHEW D. HIGGINS (Senior Member, IEEE) is a Reader at the University of Warwick, where he leads WMG's Connectivity and Communications Technology Research Group within its Intelligent Vehicles Directorate. His research interests span 5G and Beyond, Core Networking, IEEE 802.3xx, GNSS, and Timing, with applications to both the Automotive and Manufacturing domains. Coupled with an overarching motivation to ensure ongoing resilience of the domain is considered, Matthew leads many high-value collaborative projects funded through EPSRC, Innovate UK, and HVMC, as well as also leading multiple projects funded directly by industry.

CARSTEN MAPLE is a professor of cyber systems engineering at the Cyber Security Centre at the University of Warwick, where he leads the GCHQ-EPSRC Academic Centre of Excellence in Cyber Security Research. He has published over 200 peer-reviewed papers. He has provided evidence and advice to governments and organizations across the world, including being a high-level scientific advisor for cyber security to the European Commission. He is principal or coinvestigator on a number of projects in cyber security. He is Immediate Past Chair of the Council of Professors and Heads of Computing in the UK and a Fellow of the Alan Turing Institute.