Thomas R. Kurfess
Manufacturing Demonstration Facility,
Oak Ridge National Laboratory,
Knoxville, TN 37932
e-mail: kurfesstr@ornl.gov

Christopher Saldana
George W. Woodruff School of Mechanical Engineering,
Georgia Institute of Technology,
Atlanta, GA 30318
e-mail: christopher.saldana@me.gatech.edu

Kyle Saleeby[1]
Manufacturing Demonstration Facility,
Oak Ridge National Laboratory,
Knoxville, TN 37932
e-mail: saleebyks@ornl.gov

Mahmoud Parto Dezfouli
George W. Woodruff School of Mechanical Engineering,
Georgia Institute of Technology,
Atlanta, GA 30318
e-mail: mahmoud@gatech.edu

A Review of Modern Communication Technologies for Digital Manufacturing Processes in Industry 4.0

Digital manufacturing technologies have quickly become ubiquitous in the manufacturing industry. The transformation commonly referred to as the fourth industrial revolution, or Industry 4.0, has ushered in a wide range of communication technologies, connection mechanisms, and data analysis capabilities. These technologies provide powerful tools to create more lean, profitable, and data-driven manufacturing processes. This paper reviews modern communication technologies and connection architectures for Digital Manufacturing and Industry 4.0 applications. An introduction to cyber-physical systems and a review of digital manufacturing trends is followed by an overview of data acquisition methods for manufacturing processes. Numerous communication protocols are presented and discussed for connecting disparate machines and processes. Flexible data architectures are discussed, and examples of machine monitoring implementations are provided. Finally, select implementations of these communication protocols and architectures are surveyed with recommendations for future architecture implementations.
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Introduction and Background

The widespread adoption of high-bandwidth digital communication protocols combined with tremendous advances in computational speed and information storage has radically changed the manufacturing industry over the past 30 years. The shift toward intelligent and connected manufacturing processes, commonly accepted as the fourth Industrial Revolution and referred to as Industry 4.0, is the culmination of three previous revolutions focused on mechanization, large-scale production, and automation, respectively [1]. These technologies have provided the foundation for significant advances in data collection, communication, and analysis across manufacturing processes.

Digital Manufacturing technologies, the collection and application of digital information for the enhancement of the manufacturing process, have existed in the manufacturing community for the past four decades [2]. The third industrial revolution, automation of manufacturing process, served as a steppingstone by providing the mechanisms of information generation and utilization. However, this information typically remained within the same machine or process and was only used for local adjustments.

The integration of communication protocols for connectivity between disparate manufacturing and computational equipment is one of the defining accomplishments of the fourth industrial revolution, distinguishing it from previous developments in Digital Manufacturing. While the term Digital Manufacturing once referred the use of digital control components within a manufacturing line (opposed to analog control mechanisms), it now implies a much larger scope, referring to the merging of manufacturing technology, network information technology, and information analysis to provide a better understanding, coordination, and control of manufacturing processes [3]. Furthermore, the ability for hardware and manufacturing machines to communicate with computational systems has generated a new classification of equipment, cyber-physical systems (CPS), or systems that are built from and depend upon the synergy of computational and physical components [4]. Such systems have become integral to lean manufacturing by providing detailed insight into the production process. Mechanisms for advanced closed-loop control, process optimization, and quality control are among the most common applications for CPS.

The advent of CPS has subsequently driven the need to better understand computational networks and structures. During the early development of CPS, computational abilities were significantly limited by physical size and data transmission rates, requiring most data transmission to be relegated to simple file transfer in background tasks [5]. Data analysis was frequently restricted to large computational machines, distally located from the manufacturing floor, while data were aggregated and manually transferred via removable storage media. The past two decades of digital technological advancements have driven computational and data transmission capabilities to a mobile scale, where computers and low-energy communications systems are now available as a commodity. The cost of implementing such technologies has also steadily decreased, enabling access for a greater subset of the manufacturing population [6].

Increased availability of CPS, computational power, and communication mechanisms have led to the development of many similar initiatives in the field of Digital Manufacturing. Development of Digital Factory technologies and Smart Manufacturing technologies are both common terms with blurred lines of demarcation. It can be clearly demonstrated that each of these initiatives significantly overlaps. Kuhn et al. define the Digital Factory as a concept of simulation capabilities, 3D-visualization, and comprehensive data management leading to fully developed virtual models of manufacturing processes [7]. The Institute for Defense Analysis took a broader stroke in their 2012 report by defining the term Smart Manufacturing as the pursuit and implementation of Digital

[1]Corresponding author.

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Manufacturing and Digital Factory technologies that encompasses not only the shop floor but the ecosystem of manufacturing machines, data collection devices, transmission networks, and advanced modeling and feedback systems, holistically aimed at using data and information throughout the entire product life cycle to create more flexible manufacturing process [8].

Although the ability to access these technologies is a major step toward improving the manufacturing industry, transitioning the overall capabilities of Digital Manufacturing to actionable implementation decisions for manufacturing companies is another challenge entirely. Each of the initiatives above relies on significant communication frameworks to transfer information between machines and it is not immediately clear for a manufacturing company how to leverage these technologies. The availability of Digital Manufacturing technologies inherently introduces a need for a greater understanding of which methods are most appropriate and how they can be applied for beneficial changes in each manufacturing process.

This paper provides a review of specific digital manufacturing connection technologies and frameworks for communication between CPS. It aims to compare various methods of communication and provide insight into the specific strengths and weaknesses of the technique. Furthermore, it provides examples of implementation to serve as a reference for other manufacturing processes. A high-level overview of connection architectures is provided with select references for specific implementations. A discussion and comparison of specific communication protocols used as components of architecture frameworks are given. Finally, select implementations are surveyed to illustrate concepts discussed in the review.

Connection Strategies and Frameworks

The development of appropriate data frameworks, communication networks, and computational strategies for connecting CPS is an integral topic to digital manufacturing. With drastically smaller computational systems, traditional local computation is no longer the only option to store and analyze information. The development and accessibility of high-bandwidth information communication protocols have enabled distributed computing frameworks where information can be aggregated and analyzed, often physically far away from the point of generation. As a result, many terms, frameworks, and connection patterns have been used to describe the physical and network locations used in computing systems. Understanding and navigating the design decisions behind implementation choices is critical for successful industry adoption.

Distributed Computing Terminology. Cloud computing (CC), fog computing (FC), and edge computing (EC) are among the most popular terms used to describe information computation locations. Each of these three computing techniques is used to describe the physical proximity of the computation location to the data collection source. However, these terms are not intended to provide implication to the communication protocol or computational technique used for that information.

For the purposes of this discussion and from our own architecture experience, we adhere to the following convention for distinguishing between edge, fog, and cloud locations. CC, the most commercialized and publicized technology across manufacturing and other industries, refers to computations that take place on-demand at an offsite network of centralized and shared computing resources [9]. These computing resources are located in a separate physical location or building from the main data source. On the other hand, EC refers to the execution of computation at the closest location to the data source, the endpoints of either the data producer or data consumer [9]. FC traverses the edge and cloud locations by providing computational resources in the connecting networks, such as network routers, intermediate data storage devices, and other supporting hardware [9]. FC is distinguished from EC by reasonable proximity to the data producer (for example, the manufacturing machine generating the data). Computational machinery located next to the data producer for the purpose of collecting and formatting the data would be considered part of the Edge network, while a router and server used to transfer that data to another onsite location would be considered part of the Fog network. Figure 1 provides a graphical description of these terms. Although each method may be appropriate for certain circumstances, there has yet to be a universally adopted network structure. A review of the connection mechanisms between the Edge, Fog, and Cloud layers is presented in the following sections.

Connection Architecture Frameworks. Numerous studies have been conducted to evaluate different architectures for connecting CPS. Some of these architectures focus on specific levels of connectivity, such as Edge-to-Fog connections or Fog-to-Cloud connections, while others have the capability to handle complete Edge-to-Cloud communications. One widely accepted, high-level model for connecting CPS is proposed by Lee et al., detailing hierarchal levels for information communication and use. The 5C model comprises the levels of Connection, Data Conversion, Cyber, Cognition, and Configuration for connectivity and intelligent analytics in the cyberspace [10–12]. Although not specifically identified, this architecture tends to deal with the local Edge and Fog levels but can potentially be expanded to include Cloud components. The work of Monostori et al. also presents a comprehensive CPS framework, with notable inclusions of case studies about the use of Open Platform Communications—Unified Architecture (OPC-UA) and other smart connection capabilities [13]. The works in this category provide the architecture, communication protocols, and other structure toward a model for connected CPS. However, these models do not fully explore the flow of data, connectivity of the communication layers, or protocols for a multi-source implementation needed for a data-driven production process.

Other computational frameworks for Edge-to-Cloud communication techniques have been proposed that address some of these challenges. It is common for Edge-to-Cloud techniques to blend multiple communication protocols such as OPC-UA, MTConnect, Message Queue Telemetry Transport Protocol (MQTT), and Bluetooth, all within the same communication chain. Each of these communication protocols is discussed in depth in subsequent sections. An example framework blending multiple communication protocols is provided in Fig. 2. Lynn et al. demonstrate the architecture displayed in Fig. 2 with the development of a rapidly deployable monitoring system for machine tools based on MTConnect [14].

Tao et al. provide another framework relying largely on recently developed communication protocols to fill the data flow gap, demonstrating the importance of Internet-of-Things (IoT) technology, CC, and machine learning for the manufacturing industry [15]. In other studies, Tao et al. and Ferrari et al. have proposed different generalized architectures and frameworks for CPS for manufacturing applications, in which computations and analytics are performed in the cloud [16–18]. Similarly, enterprise IoT cloud service providers such as Amazon Web Services (AWS) IoT, Azure IoT, and Watson IoT, from Amazon, Microsoft, and IBM, respectively, propose computational frameworks for CPS that utilizes CC as well as EC with close coordination [19,20]. The works in this category display the importance of CC and how different architectures could be utilized to implement analytics in the edge and cloud layer; however, it must be acknowledged that the scalability and performance of these solutions often require extensive cloud resources. Appropriate use of the architectures requires vast amounts of data and computational time to train adequate machine learning models. Requirements to conduct useful analytics are frequently time-consuming and Internet-dependent. Each of these factors must be considered when balancing costs to choose the best framework for a given application.

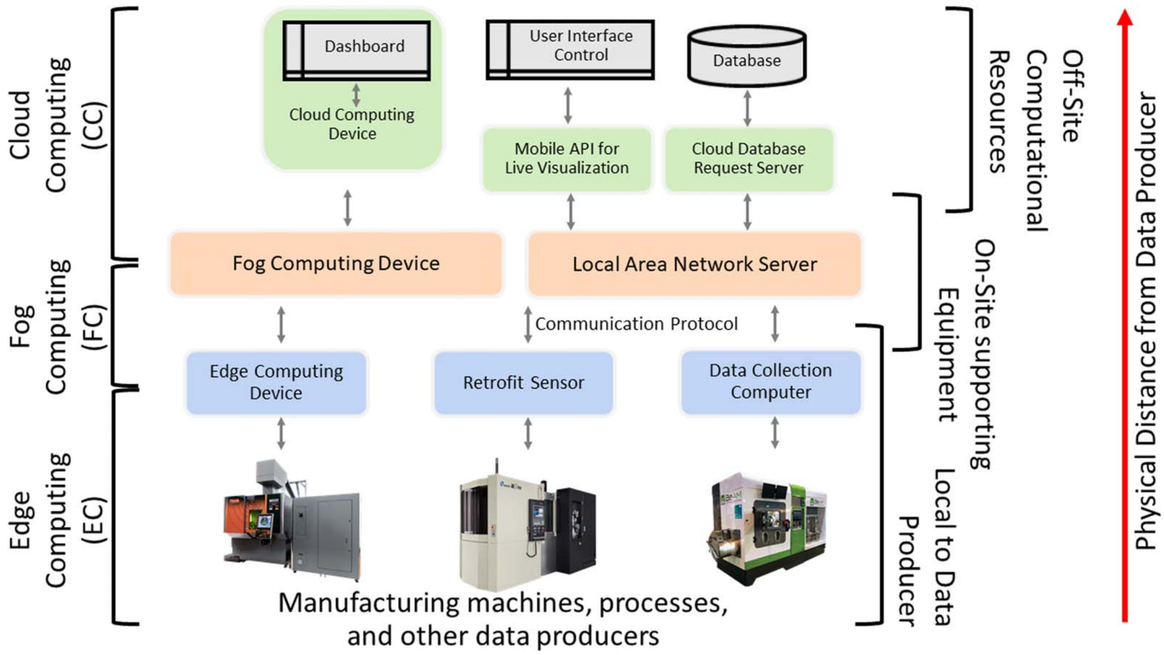

Fig. 1 Diagram of connections and physical locations of edge computing (EC), fog computing (FC), and cloud computing (CC) devices with relation to data producers. EC, FC, and CC devices are distinguished based on physical proximity to the data source.

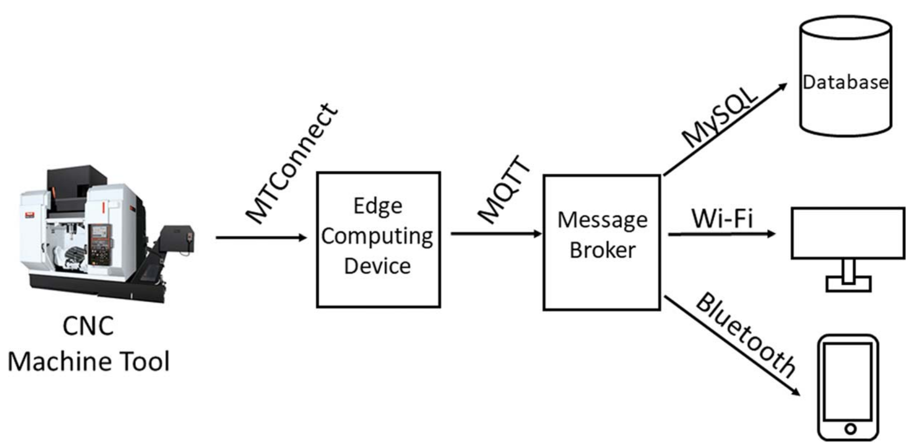

Fig. 2 Example data transmission framework with mixed communication protocols. MTConnect provides initial data acquisition that is received by the edge computing device. Data are converted to MQTT for more generic communication to the message broker. At this point, data can be sent via Wi-Fi, Bluetooth, or other communication protocols to relevant storage and analysis devices.

Manufacturing Data Acquisition Methods

Data acquisition and information communication methods in the manufacturing industry have evolved over time based on current needs and available technologies. This section of the paper discusses the efforts and technologies utilized for data acquisition over the last few decades as well as the new directions and trends driving Industry 4.0. First, communication protocols and data acquisition systems used in Industrial Controls Systems (ICS) such as Supervisory Control and Data Acquisition (SCADA) and Distributed Control System (DCS) architectures are discussed. Next, data acquisition techniques used to collect data from modern manufacturing equipment are discussed. Finally, IoT retrofit sensor solutions, as one of the most recent technologies of Industry 4.0, are discussed. The goal of implementing these technologies is to make CC and cloud communication in the manufacturing domain more seamless and affordable.

Data Acquisition and Feedback in Industrial Controls System. Since Industry 3.0, technologies such as Programmable Logic Controllers (PLC), Computer-Aided Design (CAD), Computer-Aided Manufacturing (CAM), and Computer Numerical Control (CNC) have improved the industry and helped in the development of computer integrated manufacturing (CIM) [21,22]. The DCS was introduced in the 1970s–1980s as a method of reliability to prevent the failure of one system from causing failure of the entire operational process. Under DCS, a multi-layered network is created where the granularity of control is related to the physical proximity of the controlled device. For example, the overall scheduling of production is located at the highest layer while direct control of motion is located at the lowest layer. This model provides useful lessons in reliability that can be applied with modern communication techniques.

Due to the advantages of CC, there have been studies where researchers have proposed Internet connectivity to PLCs and SCADA frameworks such as a study by Zhilenkov et al. who have discussed a power line communication based on IoT enabling PLC systems [23,24]. A study by Benias et al. presents the readiness of the industry and the potential challenges that are possible during implementation such as security issues and getting infected by different viruses in SCADA systems [25]. According to some studies, these protocols and methodologies were initially designed for communications and data exchange using local networks and they are not typically designed for nor capable of secure and authenticated communication. Thus, they are easily attackable [26,27].

Data Acquisition From Machine Tool Controllers. The Digital Factory and Smart Manufacturing concepts toward Industry 4.0 have led to several movements in the development of communication standards and protocols. The Open Platform Communications—Unified Architecture (OPC-UA) has been implemented to facilitate access to manufacturing data, among other machines [28,29]. OPC-UA was developed by the OPC Foundation for unified Machine-to-Machine HyperText Transfer Protocol (M2M HTTP) communication and industrial automation of system and processes in industries [29]. One of the strengths of OPC-UA is found in the choice to develop a platform-independent architecture that can operate on nearly any operating software, data-producing machine tool, data transmitting network hardware, or data consuming analysis hardware. It also includes significant development of permissions-based read and write access, encryption and authentication capabilities, and hierarchal address methods to facilitate the discovery of complex structures by OPC clients. This provides an extremely flexible, yet industry-ready protocol that can be modularly applied to a diverse set of manufacturing equipment and computational machines.

Unification and standardization of communication have been the goal of other recently developed standards as well, such as the MTConnect standard for machine tool communication.[2] The development of the MTConnect protocol was initiated to address the need of collecting quality measurements from built-in sensors and existing information on computer numeric controlled machine tools (CNC machines) in a standard format [30]. MTConnect is an open standard, the Extensible Markup Language (XML)-based read-only protocol that facilitates data acquisitions from manufacturing machines through a Transmission Control Protocol (TCP) connection [31]. MTConnect has been widely adopted by leading machine tool manufacturers such as Mazak, Okuma, and DMG Mori. Torrisi presents an example implementation of the MTConnect protocol on a CNC machine, investigating connection speed to create a reliable part production monitoring system [32].

Modern machining equipment is often compatible with at least one of these technologies, providing low-cost or free access to the machine's data [28,29,33]. Studies by Lei et al., Lynn et al., Vijayaraghavan et al., and Edrington et al. demonstrate various types of frameworks with MTConnect for finishing assembly interfaces, monitoring systems strategies for small- and medium-size companies, improved interoperability for machine tools, and web-based monitoring strategies, respectively [14,34–36].

Combined Information Communication Methods. An interesting paradigm exists when the MTConnect protocol is combined with the OPC-UA protocol, or when multiple Digital Manufacturing technologies are combined to create a more generalized architecture. MTConnect focuses on machine tools to handle information related specifically to the machining process. For example, newer beta versions are allowing the transfer of specific cutting tool information along with the standard usage information. OPC-UA is less equipped to handle this particular data acquisition, but it excels in the transmission of this information after it has been collected. The generalized, cross-platform compatibility of the OPC-UA protocol makes it an excellent candidate for data transmission in a distributed, decentralized network. The benefits of both protocols can be leveraged when combined; MTConnect as a method of direct data collection from the machine tool, and OPC-UA as a method of generalized information transfer immediately after collection to the final data storage location. Additional benefits are added when the base standard of both protocols is considered. For example, many versions of MTConnect enforce read-only characteristics. No protocol exists for data to be passed back to the machine tool. With OPC-UA alone, machine tools are more vulnerable to program modifications whether they are innocent or malicious. By leveraging MTConnect as the direct source of the information and OPC-UA as the Edge-to-Cloud transmission protocol, we can increase the security of machines and manufacturing equipment.

Due to the usage of standard network communications by these protocols, such as TCP/IP that are followed by the Open Systems Interconnection (OSI) model, encryption and authentication techniques can be applied to machine tool communications to increase the security and authorized access to the data [32]. The OSI model is a seven-layer communication model using an open generalization system produced by the International Organization for Standardization (ISO) that prescribes the means by which different applications and protocols may interact via a network [37,38]. In this model, Layer 1, the Physical Layer, defines the physical and electrical characteristics of the network such as the type of cable that transfers the data. Layer 2, the Data Link Layer, defines the access strategy for sharing the physical signals. Ethernet, Point-to-point (PPP) protocol and Switch are among the technologies on this layer. Layer 3 is the Network Layer, which is the main layer at which routers operate. At this layer, the network connections can be established, controlled, and terminated. It is clear that Layer 1–Layer 3 is all related to hardware layers.

The focus of communication technologies such as MTConnect or OPC-UA is at the heart of the OSI model, located on software Layers 4, 5, 6, and 7. The 4th layer, the Transport Layer, enables the reliability and integrity of the next layer, the Session Layer. Protocols such as TCP and User Datagram Protocol or Universal Datagram Protocol (UDP) relate to this layer and are detailed in the following sections. Layer 5, 6, and 7, are Session, Presentation, and Application Layers that provide data exchange between entities, formatting the data, and end-user protocols, respectively. Standards and communication protocols such as Web Sockets, XML, JavaScript Object Notation (JSON), HTTP, and MQTT, live on these software layers.

Since MTConnect and OPC-UA can only share the information given by the machine tool, the data are limited to the parameters available to the controller. The update rate of the parameters as well as the rate of transmission of the data is also limited to the hardware resources available to MTConnect. Due to these limitations, current implementations of MTConnect might not be able to provide sufficient data rates required for some high-frequency monitoring or simulation applications. However, studies have shown that many parameters such as feed rate, the velocity of the motors and spindle, load on the spindle motor, current G-Code program, current G-Code line, and many other parameters can be accessed via MTConnect that can be utilized to improve visibility and efficiency on the production line [14,34–36,39].

Information Communication Protocols

MTConnect and OPC-UA are only two of the many communication protocols, data acquisition technologies, and information strategies available for use in Digital Manufacturing frameworks. A subset of notable protocols is provided with sample applications. Similar to the combined MTConnect/OPC-UA architecture explored above, many of these communications protocols and strategies can be combined (and are even required to be combined) with others to form a larger network.

[2]http://www.mtconnect.org/

Edge, Fog, and Cloud Communication Protocols. This section reviews common information connection protocols that can be implemented to communicate within and across the Edge, Fog, and Cloud computation levels. In most applications, these technologies are used to provide information between the Edge layer, the nearest network and often physical point where data are generated, and the Cloud, the distributed and networked computational devices. However, other novel frameworks exist.

Transmission Control Protocol and Universal Datagram Protocol. Transmission Control Protocol/Internet Protocol (TCP/IP) and User Datagram Protocol or Universal Datagram Protocol (UDP) are a set of rules and procedures for Internet communications [40]. The main difference between TCP and UDP is that TCP is connection-oriented and confirms the delivery of the packets; however, UDP is a connectionless protocol and sends the packets with no delivery confirmations. Due to its structure, TCP communicates only in unicast. However, UDP can communicate in three modes: unicast, multicast, and broadcast modes. Therefore, TCP is recommended for the applications where there is a need for high reliability of data delivery and speed is not crucial. UDP, on the other hand, suits the applications where quick and efficient data transmission is more important [40–47].

Hypertext Transfer Protocol. Many, if not all, Internet-connected applications rely on the Representational State Transfer (REST) architecture [48]. This architecture resides on the Application layer of the OSI model to transfer information between information systems [49]. Typically, the Hypertext Transfer Protocol (HTTP) is used in coordination with the REST architecture. HTTP provides a structured set of actionable commands such as "GET," "PUT," "POST," and "DELETE" with which clients and servers can manipulate information [50].

Message Queue Telemetry Transport Protocol. The Message Queue Telemetry Transport (MQTT) Protocol provides additional capabilities not enabled with HTTP. MQTT protocol allows information transfer to and from multiple devices in a many-to-many fashion under a publish-subscription architecture, commonly referred to as PubSub [51]. The PubSub architecture enables a publisher to provide information directed toward a specific topic. This information is received by a subscriber listening to the same topic. Multiple publishers can provide information and multiple subscribers can receive the information, allowing for a many-to-many connection scheme. The MQTT protocol requires very little overhead (extra information needed for the communication protocol that is not related to the actual information being communicated) both for implementation on publishers and subscribers, as well as in the message itself. It is a popular choice for IoT applications and other systems requiring distributed communications. Furthermore, the MQTT protocol can be combined with other similar protocols in a single system. Similar protocols include the Advanced Message Queuing Protocol (AMQP), the Simple/Streaming Text Oriented Messaging Protocol (STOMP), and the Extensible Messaging and Presence Protocol (XMPP).

MQTT supports three levels of Quality of Service (QoS) to ensure a reliable data transmission. QoS0 is the simplest QoS that indicates the data to be transmitted (at most) once with no delivery verification. QoS1 provides one step up in reliability, ensuring that the messages are delivered at least once. However, QoS1 does not guarantee that the messages are delivered only once, resulting in the potential for multiple deliveries on the subscription side. QoS2 is the most complicated QoS in MQTT that ensures the messages are delivered exactly once. This QoS is not supported by some services due to the complexity of the infrastructure for verification required by QoS2 [52]. Communication latency of these protocols depends on many factors such as the computation power of the server computer. The latencies of MQTT in end-to-end communication in a wired network for different QoS are compared in a case study and could be used as a reference to compare the performance of these QoSs [53].

WPAN and Hardware Communication Protocols. This section introduces the technologies that are either used to communicate between sensors and edge computation devices or between multiple edge devices in Wireless Personal Area Networks (WPANs). Analog and digital data measurement devices are commonly combined with short-range communication protocols to capture data from sensors and communicate to edge devices via wired connections, while protocols such as Bluetooth, Zig-Bee, and Z-Wave, however, are suggested as WPANs that could be utilized in the industry to have local communication between two or more edge devices.

UART/RS-232/RS-485/Modbus. The universal asynchronous receiver transmitter (UART), which is sometimes referred to as transistor-transistor logic (TTL), is a serial communication protocol that is widely used, especially in microcontroller unit and microprocessor unit projects. The logic voltage for UART is usually 5VDC, which provides a reliable data transfer for short distances. Recommended Standard (RS)-485 uses a higher logic-voltage serial communication which is more suited for industrial applications where longer distances, higher reliability, and faster data communication are needed. RS-485 can be implemented on TCP and over networked interfaces such as Modbus. Modbus over TCP/IP or over Remote Terminal Unit (RTU) is the major protocol in SCADA systems to communicate with devices such as PLCs [54,55].

Analog-Digital Converter, Inter-Integrated Circuit, and Serial Peripheral Interface. Sensors and sensing modules have various methods to exchange data with platforms. Sensors are often analog, meaning that they either act as a variable resistor or generate a variable voltage proportional to their range of measurement. Data from this type of sensor can be acquired by converting the analog signal to a digital value, which is achieved with an Analog-Digital-Converter (ADC). Sensors with no analog output often communicate with digital communication protocols such as UART, Inter-Integrated Circuit (I2C), or Serial Peripheral Interface (SPI) [56].

Bluetooth. Bluetooth Low Energy (BLE), or Bluetooth 4.0, has received significant interest in recent years. In IoT applications particularly where battery management is important, BLE could become a valuable wireless communication method [57–60]. Network technologies such as mesh network topology have been implemented on wireless communications tools such as Bluetooth, enabling Bluetooth to stay among the top wireless technologies in this industry [61]. Bluetooth 5.0 provides a longer range for communication and provides additional services in addition to Bluetooth 4.0 such as more advanced device discovery, which makes this technology advantageous for IoT applications [62].

Zig-Bee and Z-Wave. ZigBee is an IEEE 802.15.4-based standard that defines communication protocols for low-power, low-data-rate, and short-range wireless communication in 868 MHz, 915 MHz, and 2.4 GHz frequencies with a maximum data exchange rate of 250 Kbit/s [63]. Z-Wave is a non-standard-based communication protocol intended to provide low-latency transmission, at the cost of only 100 Kbit/s. However, Z-wave requires less power for transmission than ZigBee [64]. Both ZigBee and Z-Wave can be used to create mesh networks similar to a Bluetooth mesh. As with other wireless communication technologies, both ZigBee and Z-Wave are approved for operation on a different range of frequencies in various countries. Implementation of ZigBee and Z-Wave must adapt accordingly to respect the regional regulations. For example, Z-Wave does not operate on standard 2.4 GHz frequencies in any country, inherently avoiding crowding and noise problems and providing a major advantage over ZigBee in some locations.

Applications for Manufacturing Processes

Manufacturing industries can more easily leverage these data acquisition, communication, and connection protocols to benefit production processes. These technologies can be used for in-depth analysis and process monitoring to improve efficiency, production throughput, and process optimization. However, the diverse range of technologies does not provide a clear entry point to implement these techniques. Various authors have attempted to bridge this gap by providing applied examples. This section provides a brief summary of the example applications of Digital Manufacturing technologies.

Hardware, Software Upgrade, and Retrofit Solutions. The decrease in cost and increased accessibility of many of the communication protocols presented allow for convenient methods to upgrade traditional manufacturing processes and equipment with modern technologies.

Brundage et al. provide a clear guide to not only implementing Digital Manufacturing technologies on the shop floor but also provides direction for how to determine where to start and which technologies may be appropriate to deploy [65]. Similarly, Wu et al. provide a comparison of machine learning technologies for Digital Manufacturing applications [66]. Finally, Mingtao et al. address secure implementations of CPS with a goal of detecting unwanted intrusion into the digitally connected machines [67].

Significant work has been developed regarding the addition of low-cost sensors and other hardware components to traditional manufacturing equipment. These additions provide increased data collection mechanisms and communication platforms. While some retrofit solutions require hardware modifications, implementation of communication and connection protocols often allow for similar if not equal capabilities through software upgrades alone. Many protocols can be implemented with only small changes to existing open-source code. For example, MQTT applications can be loaded onto standard computers that are often found sitting next to manufacturing equipment, typically used to transfer preprogrammed instructions to the equipment. The MQTT applications allow for communication out to the FC layer for data aggregation. This process only requires software changes to upgrade current systems, without the need for extra hardware or more traditional retrofit solutions, enabling enhanced Digital Manufacturing technologies.

Common platforms for low-cost hardware development include the Arduino Uno platform, Raspberry Pi, and Particle Photon.[3] Each of these platforms offers tradeoffs in power consumption, computational speed, and communication protocols. For example, typical Arduino platforms (running on the ATmega328P MCU) are convenient for standard analog and digital I/O but do not provide wireless communication protocols such as Wi-Fi or Bluetooth. However, the Particle Photon (recent models operate on the STM32 ARM Cortex M3 MCU) provides these communication protocols at the cost of higher power consumption and fewer I/O ports. Each of these tradeoffs must be balanced to find the right fit for a given environment.

Studies by Guerreiro et al. and Nsiah et al. in this category refer to IoT retrofit sensor packs as cost-affordable addressing solutions for data acquisition needs in the manufacturing industry where sensing solutions are either not available or the existing solutions and their communication capabilities do not satisfy the required accuracy, sensitivity, or response frequency [68,69]. A study by Manavalan and Jayakrishna presents the benefits of IoT enabled embedded and retrofit solutions in improving the supply chain for Industry 4.0 [70]. Civerchia et al. propose battery-powered IoT sensing devices for the development of advanced predictive maintenance applications in which the battery in their setup could last for one year with a 30 min interval publishing frequency. Studies by Tritschler, Prevost, and Saleeby propose IoT vibration retrofit platforms as machine tool health monitoring systems in which high-frequency data can be acquired from sensors and analyzed [71–73].

Process and Digital Twin Modeling Solutions. With modern developments of communication protocols and connection architectures, numerous initiatives have attempted to model physical machines, processes, and results with computational methods. These "Digital Twins" of the physical world have been developed to different extents, each modeling and predicting different areas of the production process. The concept of Digital Twin modeling is defined by Cai et al. as "virtual machine tools of physical machines for cyber-physical manufacturing by using sensory data and information fusion integration techniques" [74]. Digital Twin initiatives have been implemented to address a wide variety of modeling scenarios. Simple solutions range from open-loop monitoring of process data while more complex implementations include AI-powered feedback to correct errors in a manufacturing process [75].

Many Digital Twin methods integrate models of physical systems with information and result from both computer simulations and CPS connected data. These two sources of information are combined to provide a more accurate method of predicting the system's behavior and production results. DebRoy et al. discuss this concept by summarizing the technology needed for a complete Digital Twin to predict microstructure development, residual stresses, and part defects in additive manufacturing [76]. Knapp et al. provide part of the implementation suggested by DebRoy through the integration of temperature and velocity fields from both numerical simulation and experimental measurements [77]. Knapp's Digital Twin model for directed energy deposition in additive manufacturing provides a more accurate cooling rate and temperature gradient prediction than traditional conduction calculations [77].

Looking to the future of Digital Twin modeling where complete factories of CPSs can be connected and monitored provides exciting opportunities for process development. With more advanced capabilities to link and correlate manufacturing data from different sources, Tao et al. demonstrate a future application for Digital Twin modeling in partial and parallel disassembly sequence planning for products [78]. Implementation of the near real-time analysis for product information, timing information, and upstream/downstream events would provide beneficial flexibility and adaptability for assembly planning methods.

Discussion and Recommendations

The availability of vastly different communication protocols and connection architectures provides an uncertain path forward for many manufacturing industries. While no single connection architecture has been found to be appropriate for every application, the authors have found three best practices that can be applied to many Digital Manufacturing implementations.

The use of the MQTT messaging protocol has provided a very convenient method of communicating varied data formats across each of the Edge, Fog, and Cloud computing layers. This protocol seems to be supported by a vast number of low-cost hardware platforms such as the Raspberry Pi and Particle Photon. Additionally, the light-weight packet standard allows for very little increase in message sizes due to overhead. The authors have found this protocol to be applicable to many different manufacturing applications.

Additionally, the authors have found the MTConnect and OPC-UA standards for CNC Machine Tool information to be very useful for low sample frequency applications. While these protocols are implemented for machining processes, a clear need exists for similarly standardized protocols to be developed for other machine and process classifications, such as additive manufacturing machines, injection molding machines, and continuous manufacturing processes. There is also a need for support of increased

[3]https://www.particle.io/, https://www.raspberrypi.org/, https://www.arduino.cc/

sample frequency in the MTConnect and OPC-UA protocols on CNC machining equipment.

Finally, the authors recommend implementations of communication architectures that prioritize aggregation of collected data locally at Fog levels instead of transmitting all collected data off-site to cloud computation levels. At scale, significant costs can be incurred for manufacturing companies based on data transmission rates. While it may be relatively cheap to purchase data storage space at the Cloud computing level, it is expensive to transmit large amounts of data between local Fog layers and external Cloud layers. In other words, evaluating the costs of purchasing company-owned data storage mechanisms for Fog layer storage may save costs rather than connecting CPSs to Cloud storage.

Conclusion

Technologies developed during the previous three decades leading to Industry 4.0 and Digital Manufacturing have dramatically increased capabilities for the manufacturing community. Modern connected CPSs have enabled rapid, high-quality data acquisition while significant increases in computational capabilities have enabled greater access to these technologies. Communication protocols provided the means by which vast amounts of information can be transferred throughout different levels of an industrial network while Digital Twin capabilities enable fascinating process modeling techniques. With a diverse range of Digital Manufacturing technologies, it becomes challenging to determine which tools are best suited for a given application. This paper serves as a review of similar connection and communication technologies and provides recommendations for implementing them on manufacturing processes. Combining these technologies in new ways will certainly enable more efficient, accurate, and predictable manufacturing processes over the next quarter century.

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Conflict of Interest

There are no conflicts of interest

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request. The authors attest that all data for this study are included in the paper. No data, models, or codes were generated or used for this paper.

[4]http://energy.gov/downloads/doe-public-access-plan

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