Using EtherCAT for Industrial Control Communications

EtherCAT is an ideal solution in many motion control and related industrial automation applications because of its high speed, determinism, and reliability.

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Industrial automation engineers are constantly challenged with selecting the best electronics platforms, communication methods and software to automate a wide variety of factory machinery and production plant processes. Motorized equipment, valves, sensors and other types of electrical components are the typical devices requiring automation. Although every type of automation endeavor presents its own challenges, one of the most demanding automation sectors is motion control due to the required speed and accuracy.

Motion control is a specific sub-field of automation, where the position and/or velocity of articulating machine and robot sections are controlled using motors or linear actuators. The goal is to precisely locate fixtures, tooling and robot arms to repeatedly perform the desired functionality with a very high degree of accuracy. Motion control technology represents a vital and indispensable element for many industrial applications such as automotive assembly, mechanical operations, semiconductor production, filling and packaging, printing and many more.

High performance motion control depends strongly on communication technology. In years past, motion control was traditionally implemented with hardwired solutions or specialized, proprietary digital communications methods. These were expensive to install and sensitive to disruption.

The development of industrial Ethernet has changed this paradigm by allowing the introduction of digital communication standards and open systems. The media and protocols have been made more robust so that Ethernet can truly serve as a high-performance industrial fieldbus system for most types of applications.

Several protocols exist that are tailored to various industrial needs, and this white paper will discuss the evolution of field bus and industrial Ethernet technologies, and show how they power modern manufacturing operations in general and motion control in particular.

EtherCAT and its associated hardware ecosystem are highlighted because it is an Ethernet-based industrial fieldbus protocol in a leading position for motion control applications. The automation industry is ramping up to provide products that leverage EtherCAT capabilities for motion control and many more applications.

Limits of Fieldbus Technology

In the late 1990s, driven by increasing market requirements, many types of distributed digital control methods were developed to communicate high volumes of data quickly between central controllers and factory floor field devices such as sensors, actuators, servos and motor drives. These communication systems are generally labeled as field bus technologies, but represent many different media and protocol types.

Fieldbus has become a generic term encompassing a number of different industrial network protocols such a Profibus, DeviceNet, CANopen and others. Typically, a programmable logic controller (PLC) or personal computer (PC) serves as the fieldbus

master, orchestrating communications with distributed fieldbus slaves such as input/output (I/O) modules and other field devices.

Certain fieldbus technologies are optimized for applications or data type, and not every device may offer connectivity with every fieldbus protocol. However it is not unusual for a system to implement multiple field bus technologies simultaneously.

These traditional field bus technologies are often proprietary and require very specific hardware and installations. Because of this, component costs are relatively higher than for more standard equipment. Implementation of these technologies is typically performed by automation engineers and operations technology (OT) personnel. They are now mature technologies with a known level of reliability.

Depending on the fieldbus type and selected media, many physical fieldbus topologies are possible such as daisy-chain (or linear), star, ring, branch and tree. Another consideration is speed versus distance, where the rule of thumb is that the further a fieldbus can reach, the slower the communication rate.

Classic installation methods required a large quantity of individual conductors and cables to be installed directly between controllers and field devices. But compared to the pre-fieldbus era, fieldbus technology reduces the length and number of cables, shortens installation time and simplifies maintenance.

Perhaps the most significant fieldbus advantage is that most fieldbus devices are "smart" and offer more capabilities than their simpler brethren. Intelligent field devices typically incorporate diagnostic capabilities, and often provide many channels of data. Fieldbus technology is wildly successful, and is not only in widespread use today, but is expanding worldwide.

Market Demands Boost Ethernet

For many years, the industrial automation market has demanded improved capabilities and performance. Industrial automation platforms were historically very mission-specific and proprietary, with very little crossover to commercial-grade components. However, in recent years there have been opportunities to leverage commercial off-the-shelf (COTS) technologies in ways that make them high performers in the industrial arena. PC and Ethernet networking technologies are two prime examples.

Powerful solutions for handling more data and ever faster communication rates have particularly been in demand. One driver is the Internet of Things (IoT), where almost any consumer electronic device is becoming capable of communicating on a network. A related trend more applicable to this discussion is the Industrial IoT (IIoT), also known as "Industry 4.0", which is concerned with empowering smart manufacturing through increased networking communications to smart field devices, which are the "things" in the IIoT.

Providing real-time behavior is a networking subject specifically important for industrial communications. Whereas consumer grade applications can usually accept some level of data transmission latency, fast-moving machinery and related components must be commanded and sensed reliably to prevent failures. At the very least, the network must provide deterministic data handling and a method of time synchronization.

As good as many early fieldbus technologies were they were not able to meet these systemic requirements. Fortunately, Ethernet has developed as a solid networking method in the commercial world and a truly promising technology to take the place of industrial fieldbus technologies in the long run. How can Ethernet media and protocols be integrated as a high performance industrial motion control fieldbus?

Ethernet Takes the Networking Lead

Due to its ubiquity, high speed, simplicity, and low cost components, Ethernet has risen to prominence as the networking technology of choice for almost any consumer application. However, even with all of these benefits, Ethernet in its original form was originally conceived and designed as non-deterministic, and was therefore initially not suitable for real-time control.

Ethernet development started in the 1970s as a joint project by DEC, Intel, and Xerox. It was a simple, bus-structured transmission medium between multiple data stations in a local area. The data rate was 3 Mbps in the beginning. In 1982 this first solution emerged and became documented as IEEE Standard 802.3. In the following years there were various development steps that progressively increased Ethernet speed to over 10 Mbps and then to "Fast Ethernet" with 100 Mbps. Today, "Gigabit" Ethernet at 1 Gbps and even 10 Gbps data rates have been achieved.

The blanket term "Ethernet" describes both the hardware of the transmission medium (cables, connectors, distributors, etc.), as well as the data transmission with protocols, transmission forms, packet formats and so forth. From a detailed technical point of view, Ethernet is an explicitly specified implementation of Layers 1 and 2 of the OSI Layer Model and is widely used through the application of different protocols on higher layers e.g., HTTP or SMTP, as known from the Internet.

Standard Ethernet media and protocols are a very high performance consumer and commercial grade technology for reliably transmitting large amounts of data. In fact, Ethernet has become the preeminent networking technology throughout the world. However, the protocol allows for data packet collisions which reduce throughput and prevent guaranteed communication reliability.

Industrial Ethernet - Backbone for Automation

Further developments of various OSI model layers were necessary in order to reach the objective of making Ethernet suitable for use in industrial automation. These efforts succeeded in producing an enhanced Ethernet technology, generically referred to as

industrial Ethernet that combines the necessary high speeds with near-real-time responsiveness, all while being able to withstand the physical and electrical challenges of manufacturing installations.

Electrical connectors and components require special materials and properties to survive water, dirt and abuse on the factory floor. Shielding is necessary for the network to withstand electromagnetic interference from motors, variable speed drives, and welding. Components such as switches and adapters must be industrial-grade to handle temperature and vibration extremes. Despite these special adaptations, much of the Ethernet ecosystem is based on economical COTS technologies, or on modified versions of these inexpensive components.

Once the physical aspect was addressed, protocols required attention to provide acceptable speed with a rigorous guarantee of near-real-time throughput. Some of the major protocols distinguishing themselves in this space are EtherCAT, Modbus TCP/IP, PROFINET, and EtherNet/IP.

The results have been so successful that in recent years Ethernet-based communication networks have been established for industrial control at the system bus level as well as at the field level in manufacturing industries. Industrial Ethernet has become a de facto standard for industrial automation networking, and is now the increasingly preferred solution for factory automation and motion control applications.

Designers, engineers, and end users choose industrial Ethernet fieldbus systems for their superior price/performance ratio, enhanced abilities and widespread familiarity among employees. Since these field bus technologies are Ethernet-based, they offer straightforward office network integration and support from information technology (IT) staff.

An actual review of the overall industrial communication market for new installed systems (provided by HMS Industrial Networks, Reference 1) shows that traditional fieldbus technologies hold 66% of the market, while industrial Ethernet captures the remaining 34%.   What is more telling is that even though traditional fieldbus adoption continues to grow at 7% per year, industrial Ethernet adoption rates are increasing at a much faster rate of 17% per year.

A Common Language

In spite of standardization efforts, different Ethernet fieldbus protocols are not natively interoperable. Although many protocols can operate on a given Ethernet network, they do not readily exchange data with each other. A given field device is typically enabled for just a single protocol, and while controllers may master many field bus technologies, each interface card usually only handles one protocol. Methods do exist for bridging protocols, but these entail extra effort and expense, so it is preferable to minimize the number of protocols used in an application.

Protocols are usually supported by specific user and supplier organizations. These organizations not only promote the technology, but also ensure that standards and conformance testing are in place to ensure stable reliable performance. Some established industrial networking organizations are PROFIBUS and PROFINET International (PI), the Open DeviceNet Supplier Association (ODVA), and the EtherCAT Technology Group (ETG). When evaluating protocols and devices, it is valuable to look at the number of members in a given organization, the types of products they offer, and how actively each member participates.

For industrial Ethernet protocols, the main players grouped closely at the top are PROFINET, EtherNet/IP and EtherCAT. The rest of the market is split among many protocols, with Modbus TCP and PowerLink being the most notable.

Developing a list of goals and priorities is needed to sort out which protocol fits a given need. Required speed and data types are always important, but ensuring that the desired devices are compatible with a given fieldbus and controller is probably the top consideration. Of course, a cost justification is typically also necessary.

EtherCAT Takes the Lead

EtherCAT is considered to be the fastest real-time industrial Ethernet network available, which is natural considering that short cycle time was the main focus during the design of this protocol. Originally developed by the German automation company Beckhoff, EtherCAT is now supported and further developed by the EtherCAT Technology Group (ETG) with around 3000 members worldwide. EtherCAT actually stands for "Ethernet for Control Automation Technology", although it is also known as "the Ethernet fieldbus".

When it comes to motion control applications, speed is king, making EtherCAT a natural fit. Of course, EtherCAT is also suitable for interfacing many other types of slave field devices such as motor drives, I/O systems, sensors, valves, vision systems and mechatronic components.

EtherCAT provides, besides a number of other benefits, two features that are especially needed in motion control networks:
1. Very high data transmission efficiency, and

2. High speed and high accuracy clock synchronization.

Refer to the Table for a summary listing of EtherCAT benefits.

Table: *EtherCAT Benefits*
- Fast and deterministic; very short cycle times
- Free and open protocol with a large, strong standards association
- IEC standard
- Testing ensures conformance and interoperability
- Supports master-slave and peer-peer communications
- Operates on standard Ethernet using any topology

- Offers hot-swapping and redundancy options
- Extremely high precision system time synchronization for motion control and other demanding applications
- Slave devices use inexpensive components
- EtherCAT Plus OPC UA supports Industry 4.0 convergence of information and automation technologies
- A large ecosystem of EtherCAT-capable PLCs, PCs, I/O, and other field devices is available

Following are some more specifics.

- EtherCAT is an open, high performance industrial Ethernet technology. Introduced in 2003, EtherCAT has been internationally standardized since 2007 in IEC 61158 and 61784 and ISO 15745-4. This means any supplier is free to use the technology in a compatible form, but is obliged to not change EtherCAT to suit individual needs and make it incompatible with other suppliers' components. This structure enables EtherCAT to remain both open and compatible, although further development can be performed under the responsibility of the ETG.

- EtherCAT´s key functional principle is how it processes Ethernet frames. Each node reads the data addressed to it and writes its data back to the frame while the frame is already moving through the device (Figure 1).
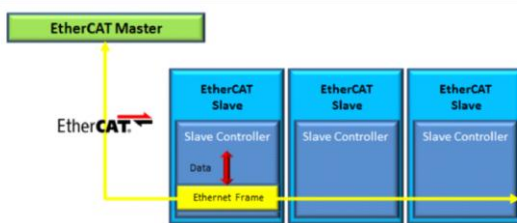

Figure 1 - EtherCat Processing of Ethernet Frames

This overcomes Ethernet's inherent system limitations because the data frame ("packet") is no longer delayed at every node, leading to improved bandwidth utilization with one frame per cycle often being sufficient for communication. EtherCAT thus becomes very fast and high performance protocol.

- EtherCAT is suitable for both centralized and decentralized system architectures. It can support master-slave, master-master and slave-slave communication as well as incorporate subordinate fieldbus systems.

- With its flexible topology (line, bus, tree, star or any combination thereof) EtherCAT can support thousands of devices without any restrictions in topology. Fast Ethernet media allows a distance between two devices up to 100 m, and greater distances are possible by using fiber optics. Hot connecting and hot swapping as well as ring topology redundancy are other important features.

- EtherCAT supports common Ethernet technologies without affecting the network's real-time capability. The "Ethernet over EtherCAT" protocol transports FTP, http,

and TCP/IP. Functional safety is built directly into the bus using Fail Safe over EtherCAT.

- The Distributed Clocks mechanism is used to provide highly precise time synchronization among slaves in an EtherCAT network, which is equivalent to the IEEE 1588 Precision Time Protocol standard. By using distributed clocks, EtherCAT is able to synchronize the time in all local bus devices within a very narrow tolerance range. All EtherCAT slaves are provided with an internal "system time" clock, while one slave acts as the "reference time" clock and distributes this time cyclically.

- EtherCAT takes conformance and interoperability very seriously. In addition to requiring a conformance test for each device implementation, the ETG offers a wide variety of activities to ensure interoperability between EtherCAT master and slave devices.

EtherCAT slave devices use inexpensive EtherCAT Slave Controllers (ESC) in the form of an ASIC or FPGA, or integrated in a standard microcontroller. Simple slave devices don't need an additional microcontroller, because inputs and outputs can be directly connected to the ESC. For more complex slave devices, maintaining communication performance depends only minimally on the microcontroller performance, and in most cases an 8-bit microcontroller is sufficient.

Since 2009, the EtherCAT protocol portfolio has also included the EtherCAT Automation Protocol (EAP). Thus, EtherCAT also allows Ethernet communication among control systems, as well as to supervisory systems. EAP simplifies the direct access of process data from field devices at the sensor/actuator level, and also supports the integration of wireless devices.

At the factory level, the base protocols for process data communication have been part of the EtherCAT specification from the very beginning. In 2009 ETG enhanced those with services for the parameter communication among control systems and for routing across system boundaries. Uniform diagnostic and configuration interfaces are also part of the EAP.

EtherCAT Supports Industry 4.0

Industrial automation continues to grow and develop as new technologies and concepts are introduced. Not only are IIoT devices becoming more numerous, but other trends like machine-to-machine networking, low-cost sensors and wireless connectivity are becoming commonplace. Real-time communication systems with multi-processing capabilities are required run adaptive systems and provide optimal control of equipment. New software applications will support wireless sensors and distributed peer-to-peer networks, which act as small operating systems that allow nodes to communicate with each other. Factories and processes will be increasingly configurable and flexible. All of these factors demand a solid networking backbone, which EtherCAT is positioned to provide.

The vision for fully automated manufacturing includes the ability for customers to order online with electronic transactions, while intelligent machines and robots respond to smoothly and rapidly fabricate customized products in batch sizes as small as one unit. This involves direct access through fast and reliable communication systems to all network-connected automation components – controllers, switches, valves, motors, drives and more. Again, high performance EtherCAT-compatible hardware components can use this communication technology to meet these needs.

Another core premise of Industry 4.0 is enabling the convergence of information and automation technologies into an accessible and seamless real-time communication stream. Toward this end, the ETG and the OPC Foundation have recently agreed to cooperate and maintain close ties (Reference 2).

OPC defines a platform-independent standard for secure and reliable data exchange among products from many suppliers, so it's very complementary to EtherCAT. Whereas EtherCAT specializes in real-time data gathering capability at the plant floor, OPC UA empowers secure and scalable communications of this data up to higher level systems. Indeed, while good links among factory controllers and devices is crucial, the next step of a modern automation system is to extend these open communications up to the enterprise level (Figure 2). This is where factory and field data can be aggregated and analyzed by the manufacturing execution system (MES), providing real-time insight into manufacturing operations. Live data is also important for incorporation into enterprise resource planning (ERP) systems so they can act upon material usage and production capabilities. As a final stage, this information can then be directed to the cloud for further analysis.
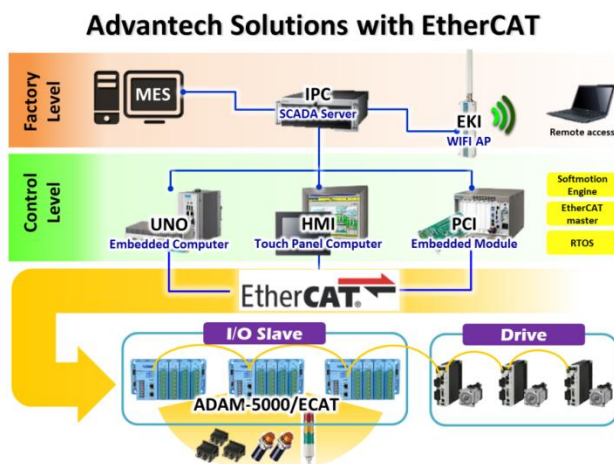

Figure 2 - EtherCAT Links Field Control Up to the Enterprise Level

EtherCAT-capable devices are ideally suited for handling plant floor and machinery interconnections. Many PC-based control solutions, supervisory control and data acquisition packages, and remote/web access options are available to run on these hardware platforms using OPC UA.

Another Industry 4.0 fundamental concept concerns the definition of a Cyber Physical System (CPS). A CPS is composed of various physical and computing components that interact through embedded communication capabilities. Information from different perspectives is monitored and synchronized between the physical factory floor and the cyber computational space.

By applying advanced analytics to this "pool" of information, networked machines will be able to perform more efficiently. CPS will gain increasing interest and importance in the manufacturing industry as a method of improving autonomy and reliability for automation systems (Reference 3).

EtherCAT supports level 1 of the CPS 5C pyramid architecture (Figure 3). At level 1, the "Smart Connection level", accurate and reliable data from machines and related components is acquired and communicated to the cloud. This is the foundational step in developing a CPS application, and EtherCAT is a powerful technology to support this implementation.
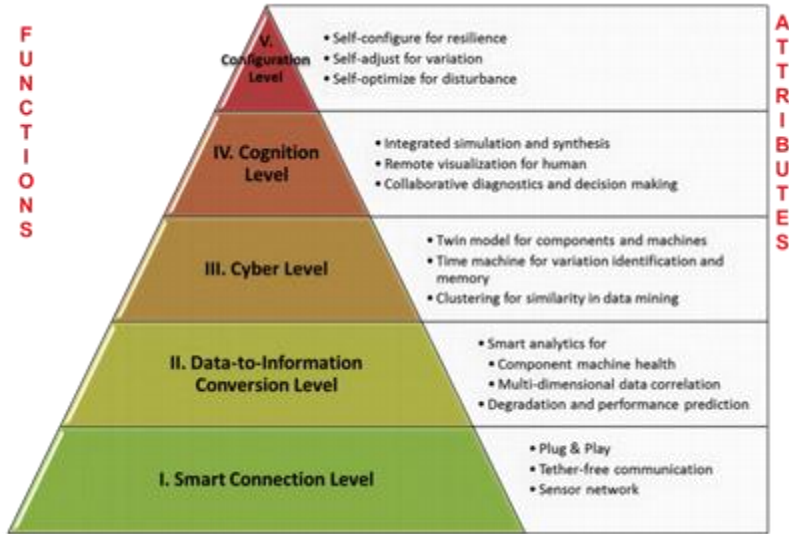

Figure 3 - The CPS 5C Pyramid Definition

PC-Based Motion and I/O Control with EtherCAT

In the general automation market, PLC-based platforms have held the leading position since their introduction in the 1970s. A significant reason for this has been the robustness of the product, which offers consistent performance even in the most challenging industrial environments.

While PLCs originally only offered basic relay-replacement functionality, they evolved to include much more advanced capabilities such as motion control, PID process control and integrated safety. The most recent developments include the adoption of some PC features such as a web servers and networking utilities. In fact, the most capable PLCs have now been assigned the title of process automation controllers (PACs) to indicate their extended abilities.

For many years, PCs have served as an operator interface platform for PLCs. Another trend which began in the late 1980s was using PC-based platforms for real-time control, replacing PLCs, and often doing double duty as the operator interface platform.

PCs offer improved processor technology along with decreasing component costs as compared to PLCs and PACs. Furthermore, PCs are ideal for performing complex calculations and offer large data handling capabilities. Originally, PCs couldn't offer the reliability of a traditional PLC. However, the development of real-time kernels and specialized soft-PLC software has empowered PCs to support more critical tasking and control algorithms. The number of automation applications utilizing a PC is on the rise.

Rather than one technology prevailing over the other, PLC, PAC and PC-based control technology have coexisted in the marketplace, and are in fact converging to some extent. For now, each technology offers certain strengths and capabilities, and end users have more choices than ever when selecting automation platforms. Some suppliers offer multiple solutions to provide a wide spectrum of options (Figure 4).
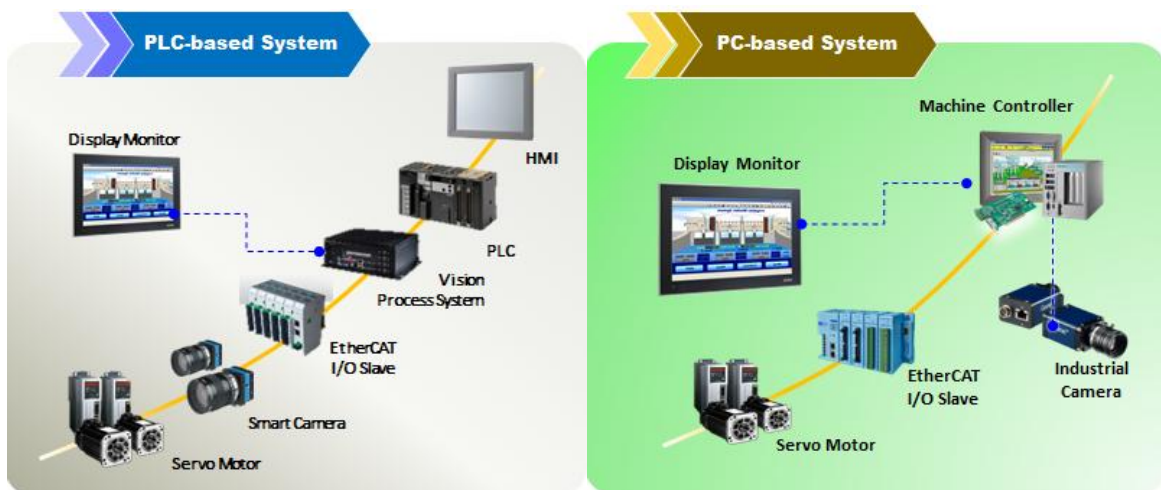

Figure 4 - PLC-Based and PC-Based Automation Solutions

EtherCAT in the Real World

Out in the real world, EtherCAT can be the enabling technology that lets a machine or robot builder OEM provide an effective product at an economical price. Consider a packaging machine with on-board motion controls for moving and orienting products

A designer could go the traditional route, choosing a standalone PLC, connecting it to conventional servo drive motion controllers via a proprietary field bus, hardwiring in whatever I/O is needed, and supplying a separate operator interface PC.

But drawing from the EtherCAT ecosystem, there are some more attractive options. For instance, a PC-based machine controller with native EtherCAT communications offers a more consolidated and integrated approach. The PC-based solution provides high computing power from a scalable CPU, and of course very low-cost storage and memory.

Not only that, but the operator interface functionality can be implemented natively on-board the PC, obviating the need for a separate component.

EtherCAT communications will work reliably with any number of motion controllers, ensuring compatible high-speed connectivity. The balance of this machine would likely have many traditional I/O points, which would easily be integrated with EtherCAT I/O devices located as required around the machine. Pushing the I/O devices out on to the machine reduces the amount of hardwiring required, and provides the opportunity for field device diagnostics.

Choosing EtherCAT technologies allows the designer to collapse the automation platform into a more economical and tightly integrated configuration, using fewer products. Cost goes down and performance goes up. Fewer products and a proven protocol mean less integration risk and better compatibility.

Conclusion

As Ethernet-based technologies continue to accelerate into the industrial automation workspace, it makes sense that hardware and software optimized to meet factory and process control needs will take the lead. The EtherCAT industrial fieldbus protocol represents a leading method to extract maximum performance from the commercially available Ethernet platform. EtherCAT is able to successfully empower motion control applications, which have traditionally been a demanding specialty, as well as other critical component such as vision systems.

A large ecosystem of EtherCAT-capable PLCs, PCs, I/O, drives and other field devices makes implementation of this protocol straightforward for designers and engineers. Furthermore, combining EtherCAT's plant floor connectivity with OPC UA's data exchange capabilities allows these two complementary technologies to securely communicate data from the plant floor up to higher level MES and ERP systems.

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