EtherCAT-enabled Advanced Control Architecture

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Abstract – **EtherCAT is becoming quickly adopted globally by the semiconductor, solar and FPD manufacturing industries. This Industrial Ethernet technology is an acknowledged SEMI standard that provides extraordinary real-time performance and topology flexibility, while meeting or even undercutting traditional fieldbus cost levels. EtherCAT enables advanced control architectures: instead of closing the high performance control loops locally in the peripheral devices, EtherCAT gives one the option to control even high speed processes over the bus and thus overcome limitations of the legacy approaches. EtherCAT enabled controls have simplified interfaces and limit supplier dependencies while giving access to previously closed embedded control algorithms.**

I. INTRODUCTION

The performance and bandwidth limitation of classical fieldbus systems such as DeviceNet, Profibus, CC-Link, CANopen, or Modbus dictate the control architecture of semiconductor tools and fab automation systems. For example, high speed control loops such as the position and velocity control loops of a servo drive, the MFC control loop, or even temperature control loops are closed inside the peripheral devices; the communication system is used to parameterize the trajectory control algorithm or the MFC internal control loop and to send commands which are then executed locally on isolated embedded microprocessors.

EtherCAT overcomes these limitations of the classical fieldbus systems. Due to its unique functional principle – processing on the fly – it makes full usage of the 100 Mbit/s Ethernet bandwidth and enables bus cycle times in the µs range instead of the ms range. Together with the superior performance of modern PC-based control systems, this allows one to close the control loops over the fieldbus that previously had to be closed locally in the peripheral systems.

II. EtherCAT Overview

EtherCAT is an Industrial Ethernet technology standardized by SEMI [1], IEC [2,3] and ISO [4], which was introduced to the semiconductor industry in 2004 [5]. The EtherCAT Device Protocol functional principle is an important differentiator to other Ethernet solutions: with EtherCAT, the Ethernet packet is no longer first received, then interpreted and copied as process data at every connection. Instead, the Ethernet frame is processed on the fly (Fig. 1): the EtherCAT Slave Controller chip in each slave node reads the data addressed to it, while the frame is forwarded to the next device. Similarly, input data is inserted while the frame passes through. The frames are hardly delayed at all. The frame sent by the master is passed through to the next device until it reaches the end of the segment (or branch). The last device detects no additional devices connected to the downstream port and therefore sends the frame back to the master.

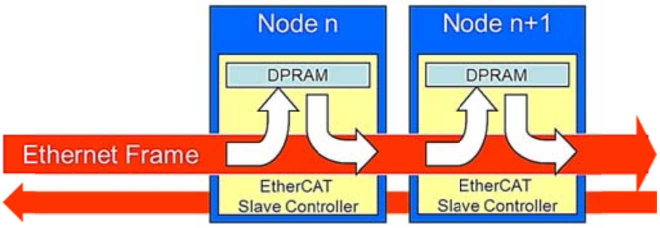

Figure 1 Frame Processing On-the-Fly

Bandwidth utilization and performance

EtherCAT populates the data of many devices in both the input and output direction within one Ethernet frame. The actual bandwidth utilization of the media increases to over 90%. The full-duplex features of 100BaseTX are fully utilized, so that effective data rates of >100 Mbit/s (>90% of 2 x 100 Mbit/s) can be achieved. EtherCAT is not only substantially faster than traditional fieldbus systems, but is also considered to be the fastest among the industrial Ethernet solutions. Typical EtherCAT cycle times are 50-250 µs, while traditional fieldbus systems take 5-15 ms for an update.

Synchronization

For synchronization of the networked nodes, EtherCAT employs the accurate alignment of distributed clocks. In contrast to fully synchronous communication, where synchronization quality suffers immediately in the event of a communication fault, distributed aligned clocks have a high degree of tolerance from possible fault-related delays within the communication system.

With EtherCAT, the data exchange is completely hardware based on "mother" and "daughter" clocks. Each clock can simply and accurately determine the other clocks' run-time offset because the communication utilizes a logical and full-duplex Ethernet physical ring structure. The distributed clocks are adjusted based on this value, which means that a very precise network-wide time base with a jitter of significantly less than 1 microsecond is achievable (Fig. 2). This accuracy is ideal for synchronized motion control applications and for integration of measurement tasks within the same network.

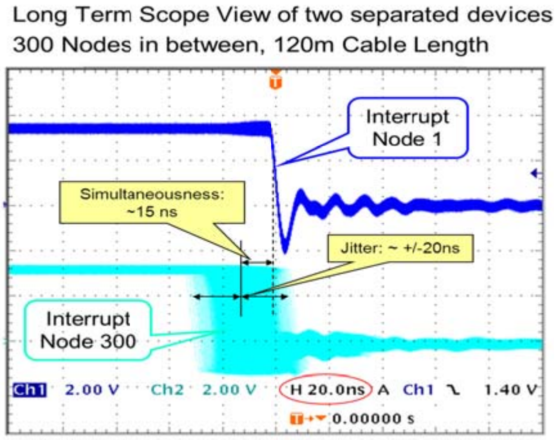

Fig. 2. Distributed Clock Accuracy Example

Cost considerations

EtherCAT masters are typically implemented in software on standard Ethernet ports, without the need for a dedicated communication coprocessor. On the slave side the highly integrated slave controller chips implement all time critical functionality, so that powerful microcontrollers are not required. On the infrastructure side EtherCAT does not require switches or other active infrastructure components and uses standard cabling and connectors. Setup and engineering effort is also reduced, since network tuning is not required any more. Furthermore, the diagnosis features of the technology provide exact error localization and thus less trouble shooting time.

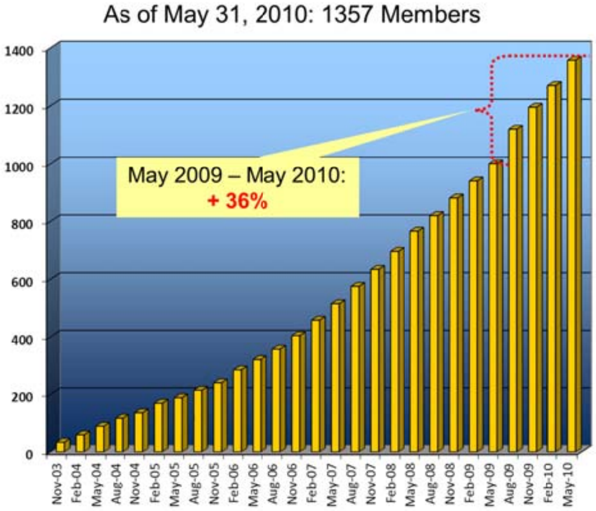

Fig. 3. EtherCAT Technology Group Membership Development

EtherCAT Technology Group

Besides low hardware costs there is another crucial factor for low component prices: worldwide acceptance of the technology, wide choice of products and thus competition among the suppliers. EtherCAT is supported by the EtherCAT Technology Group, with over 1300 member companies from 50 countries the world's largest and fastest growing Industrial Ethernet organization (Fig. 3). EtherCAT also has the fastest adoption rate among the Industrial Ethernet technologies. The product guide on www.ethercat.org already features over 200 entries with over 500 products, and many more products are about to enter the market.

Topology Options

EtherCAT networks have no practical limitations regarding the topology: line, star, tree, redundant ring and all those combined with up to 65535 nodes per segment (Fig. 4). In case the 100m distance between two 100BaseTX nodes is not sufficient, fiber optic cables are used to extend the length to 2km. The hot connect functionality allows one to connect and disconnect nodes or e.g. entire process chambers during runtime.

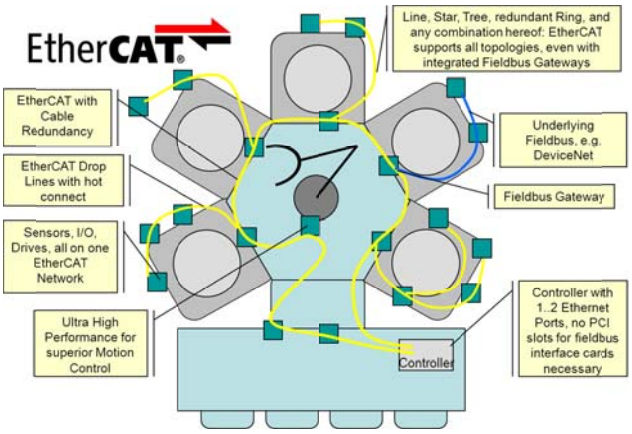

Fig. 4. Topology Flexibility with EtherCAT

Internet Technologies at device level

The EtherCAT Device Protocol can transport other Ethernet-based services and protocols on the same physical network. Such Internet technologies are tunneled via the EtherCAT protocol, so that the real-time characteristics are not impaired. Therefore, all internet technologies can also be used in the EtherCAT environment: integrated web servers, SECS/GEM, EDA, HSMS-SS, FTP transfer, etc.

Safety over EtherCAT

In the interest of realizing safe data communication over EtherCAT, the Functional Safety-over-EtherCAT protocol (FSoE) has been disclosed within the EtherCAT Technology Group. EtherCAT is used as a single-channel communication system for transferring safe and non-safe information. The transport medium is regarded as a "black channel" and not included in safety considerations (Fig 5). A safety frame containing the safe process data and the required data backup is included in the EtherCAT process data. This "container" is safely analyzed in the devices at the application level. Communication remains single-channel. This corresponds to Model A from the Annex of pre-IEC 61784-3.

The Safety-over-EtherCAT protocol has been assessed by the German Technical Inspection Agency (TÜV). It is certified as a protocol for transferring process data between Functional Safety-over-EtherCAT devices up to SIL 3 according to IEC 61508. The implementation of the Safety-over-EtherCAT protocol in a device must meet the requirements of the safety target. The associated product-specific requirements must be taken into account.

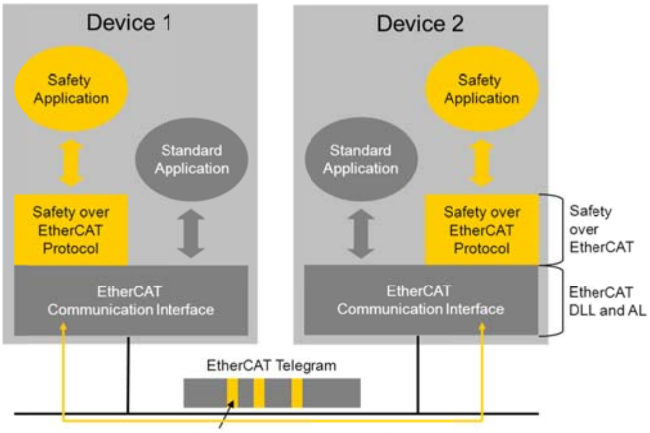

Fig. 5. Safety over EtherCAT Software Architecture

EtherCAT Automation Protocol

The most recent addition to the EtherCAT technology is the EtherCAT Automation Protocol (EAP, Fig. 6). EAP combines Ether CAT protocols with classical Ethernet topologies for interconnecting EtherCAT masters, configuration tools and wireless components. While the EtherCAT Device Protocol – with processing on the fly – operates fully deterministically, typically in the microsecond range, EAP cycles are in the millisecond range.

III. Classical Control Architecture

In the past, high speed control loops had to be closed locally inside the decentralized devices or via specialized and proprietary motion bus systems. Both the performance of general purpose fieldbus systems and the performance and capacity of the central control unit did not support other solutions.

This classical approach has several disadvantages:

1. "Black Box" Problem: the control algorithm inside the peripheral device is determined by the manufacturer of the device and not accessible by the equipment maker. This means that the tool vendor or system supplier cannot differentiate himself from competition by advanced control methodologies. Development cycle time for custom, IP-rich applications become prolonged by the iterative nature of the vendor-customer design process.

2. *Complex Communication*: the local control algorithms require a large number of parameters; managing device configurations on large networks is difficult and often manufacturer specific. Setting parameters e.g. in a gas panel becomes a lengthy process involving custom utilities. Each "intelligent" peripheral device comes with a specialized configuration tool (e.g. drive setup and parameterization tool) which has to be installed, maintained and operated.

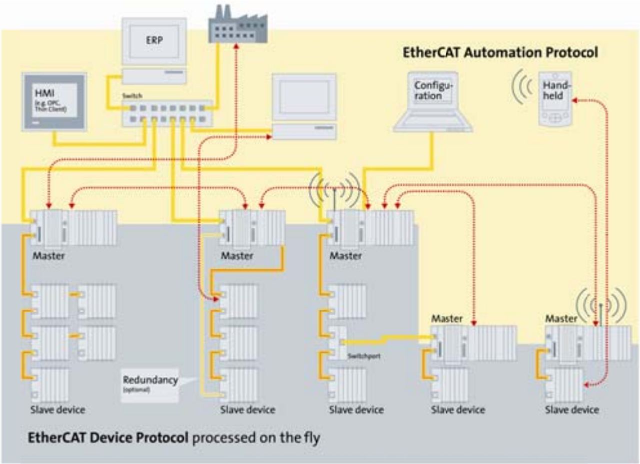

Fig. 6. EtherCAT Automation Protocol

3. *Supplier Dependency*: due to the complex interfaces and large number of parameters it is difficult and costly to exchange one supplier for another. This results in high costs for the peripheral devices.

4. Process Control Loops Interdependency Problem: the control loops inside isolated dedicated controllers have limited means to synchronize or coordinate the process control knobs e.g. implant dose to target wafer position control, plasma density control. In general, no model-based process control is efficient via classical fieldbus.

IV. Advanced Control Architecture

The combination of the EtherCAT performance with the processing power and capacity of modern PC-based control units enables a new control architecture approach. Not only parameters and commands for decentralized controllers or data of relatively slow control loops can be communicated over the bus system, but also the data for high speed control loops.

Handling the control algorithms by a central CPU opens the "Black Boxes" of the past: new advanced algorithms can be developed, tested and finally implemented in the tools easily without involvement of the subsystem supplier – and without sharing the results with competitors.

Also the bus interface is simplified substantially: instead of a complex and manufacturer specific configuration parameter set, just simple and lean command/actual values are exchanged, together with standardized command and status words. The drives, temperature controllers, MFCs etc. become leaner and thus lower cost, and the supplier dependency is minimized.

V. Example: Servo Drive Control

The EtherCAT servo drive parameters and behavior are standardized by IEC in [7]. The Drive Profile Working Group within the EtherCAT Technology Group has elaborated an implementation guideline for servo drives that makes use of the Advanced Control Architecture. All three servo drive modes described in this guideline (Cyclic Synchronous Torque, Cyclic Synchronous Velocity, and Cyclic Synchronous Position) close the control loop over EtherCAT. The path planning and motion coordination is executed within the network controller’s central CPU, for instance a PC (Fig. 7). Drives supporting these modes have a very small local parameter set (object dictionary) and are very simple to configure.

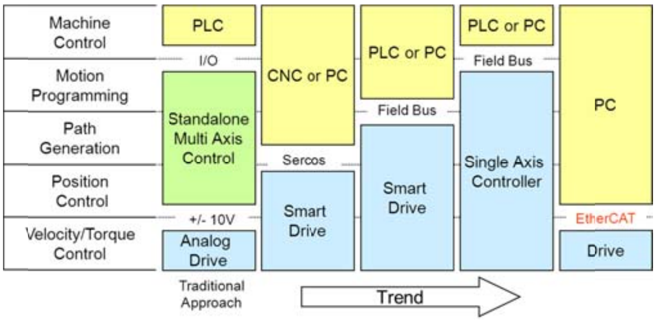

Fig. 7. Trend for Drive Control Architecture [8]

Drives built around classical controls and/or low performance Ethernet fieldbuses rely on trajectory control generation / path planning in the drive itself, and often require special drive-to-drive communication channels outside of the normal scan rate in order to coordinate the axes to each other. These drives themselves are much more complex and therefore more costly to develop than a typical EtherCAT drive, which can be developed with less intelligence on-board, yet give better performance.

An indicator for the complexity of the drives and their configuration with or without local path planning is the size and content of the cyclic process data assembly. In Fig. 8 the CIP Motion [9] and EtherCAT process data layouts are shown. Note that originally [7] CIP Motion was using an assembly of 120 Bytes; this was changed in 2009.

The combination of ultra fast and deterministic industrial network supporting I/O devices, motion axes, specific semiconductor process control devices and processing power of multi-core processor opens up unlimited possibilities for advanced process control at a very modest cost compared to any other existing industrial solution for process control. It is not a purpose of this paper to provide detailed research into different kinds of control algorithms that become feasible due to the nature of the new control architecture. However, it would be prudent to outline a few control domains that are not typically easily implementable today due to isolation of local control loops inside dedicated devices.

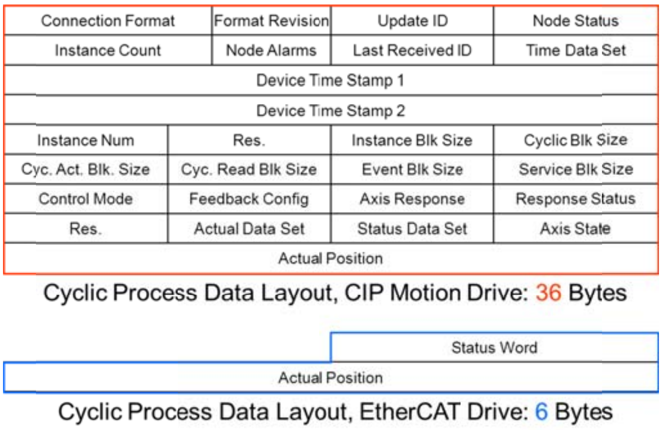

Fig. 8. Process data assemblies of drive profiles: drive internal path planning (CIP Motion) vs. path planning in central controller (EtherCAT)

Conformance Testing

The EtherCAT conformance test tool covers the servo drive profile according to the implementation guideline and checks the corresponding objects, as well as all other standard EtherCAT slave behavior. Implementing a servo drive with EtherCAT becomes a much easier task and less costly undertaking.

VI. Advanced Process Control

Loop-to-Loop Feed Forward control

It is a very typical scenario when a set point is given to a device (MFC), the device implementing its function will change the physical environment in process cavity (gas flow will change pressure), and another device responsible to maintain the process environment will then start to servo towards its set point bringing the process environment to prior or desired equilibrium (automatic pressure controller or throttle valve to maintain pressure). In this example one control loop changes the process environment and then other control loop reacts to that change. No matter how precisely the second loop is tuned, the above action will result in local disturbance of process conditions. While being a negligible effect in the past at larger technology nodes, this effect become more noticeable today with the tendency towards atomic layer films. The EtherCAT enabled control architecture addresses this issue by naturally providing instant sensor data, command set point value, etc. from one control loop to another via a feed forward link. It should be noted that it is not necessary even to have both control loops implemented on a central control computer. The same technique with some limitations can be realized on devices with local control loops by taking advantage of EtherCAT’s fast data cycle time and determinism.

Model-based/Multivariate Control

There are many examples of process control challenges in the semiconductor industry when direct measurement of a process critical physical phenomenon is not possible or cost prohibitive, e.g. direct plasma density measurement. Control techniques in such cases rely on the characterization of “process window” being defined and maintained during wafer processing by a combination of other indirect control loops. The limitation of such control types stems from the fact that different control loops and their deviation from the optimum have different impacts on critical process parameters also called critical dimension or CD. In other words, the multi-dimensional “process window” has a complex shape and can be more forgiving for deviations in one direction and highly restrictive in the other.

Traditional control architecture assumes independent control loops for pressure, temperature, gas flow, RF power, etc. It is virtually impossible to have model based control in such an architecture, since it requires multiple cross links between “control loops”.

The centralized architecture with a powerful multicore CPU along with a fast industrial network is a game changer for such control needs. There is plenty of computational power available on the central controller for complex and math-heavy control algorithms. At the same time, the EtherCAT network provides a deterministic data highway for sensor data and actuator control. The ability to control remote devices with high data rate is especially important in semiconductor systems where some critical devices like RF generators and PVD plating power supplies are located away from the actual process tool and often on another floor in the fab building.

One simple but good example of model-based control is the multi-zone highly uniform temperature control of the wafer pedestal for lithography track tools. The temperature uniformity has to be maintained within 0.05-0.1 degree C across the silicon wafer at the 150-200 degree C level. Typically, heating pedestals with 4-6 circular heating zones are used. The challenge of control is in the thermal cross talk among resistive heaters. Also, the introduction of fresh, colder wafers on the pedestal results in highly dynamic temperature transient. Traditional temperature control methods do not yield very stable results. The answer is found in model-based control when heat generation and heat transfer from zone to zone and to wafer are all taken into account for calculating resulting control signals for zone SCR’s. The only way to implement model-based control for fast changing dynamic processes today is to design dedicated local controllers with a decent microprocessor and dedicated I/O onboard. It is quite possible to do it this way, but with the process chamber count per track system reaching few tens of units, it becomes very costly to have dedicated chamber controllers. It should be noted as well that this example is well-known and not overly complex in nature.

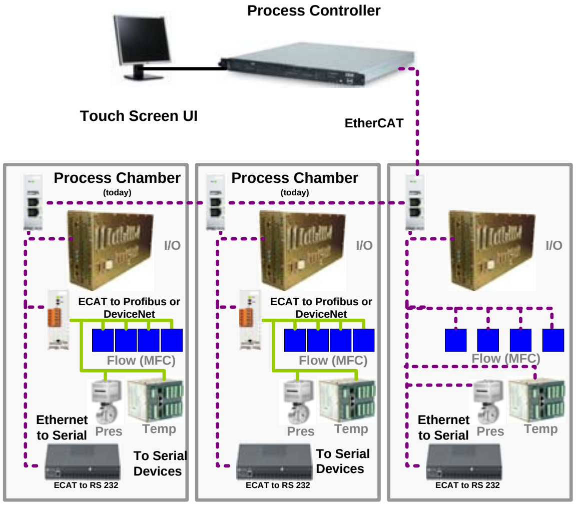

Fig. 9. EtherCAT-based Control Architecture

More complex model-based algorithms today would require a dedicated PC controller per process module, increasing the cost of this approach even further. It happens not because of the computational limitation of a modern PC controller, but because of the local I/O limitation out of a PC either due to high I/O count or unmanageable cumulative system electrical cabling, or both. The proposed new EtherCAT-based architecture with a centralized PC controller overcomes these limitations. For instance, it can handle multiples of multi-zone model-based temperature software control loops for the entire system out of a single PC controller and with reduced cabling.

Process Control Synchronization/Measurement Artifact Rejection

There are many cases when two or more different control loops, or a control loop with a system event, need to be precisely synchronized either at the start or along their trajectory. There are also cases when, due to the mechanical layout of the system or the measurement nature, a control loop feedback sensor gets temporarily affected by another unrelated part of the system.

Example 1: Lamp power modulation relative to angular position of rotating wafer pedestal. The need here is to synchronize the lamp power controller with the encoder reading for the pedestal axis.

Example 2: The temperature read back from a wafer heater thermocouple gets temporarily affected by a scanning laser producing additional local heating waves in RTP applications.

These are just two simple examples. There are plenty more of such synchronization tasks that process control engineers struggle with balancing materials cost pressure with available off-the-shelf process control solutions. EtherCAT networking virtually eliminates such challenges via its speed and determinism. The central PC controller has the full system state update instantly every scan cycle, all axes positions, all actual flows, pressures, RF power, etc. With very little effort even simultaneous data sampling can be achieved. Different control tasks can use any of the system state data to their benefit in any way desired without any additional HW design effort.

Fig. 10. Applied Materials Semiconductor Tool with EtherCAT controls

Data Collection

Nominal data collection of system and process variables and events is common place in today's semiconductor industry. The data collection rates are called out by SEMI standards and typically are within 10-100Hz at best for fielded tools. However, some of the applications or troubleshooting efforts can benefit or require much higher data rates. It is not uncommon for an MFC vendor to hook up a data acquisition tools directly to service port on MFC for troubleshooting or fine tuning. It is also not uncommon to see highly priced in-line data collection devices with local memory for detecting and saving data trace of plasma arcing or RF power disturbance, etc. Yet this is another benefit of the EtherCAT network – it can help collecting the data as fast as with 20 KHz update, while other slower devices co-exist on the same network. Moreover, neither faster nor slower devices need to be designed in a special way from an EtherCAT compatibility stand point. Indeed, faster devices have to be fast enough inside to produce fresh data at those maximum speed rates.

VII. Conclusion

So far, enhanced process control requirements were met by more powerful and more complex decentralized control devices. This has led to increased dependencies from the suppliers of these intelligent subsystems.

With the combination of EtherCAT and PC-based controllers this trend can be reversed: subsystems and their interfaces are simplified and the process control engineers are in control again.

EtherCAT enables advanced control architectures that open the black boxes of the past and introduce improved process control capabilities. At the same time, EtherCAT supports the classical approaches as well. It is up to the tool manufacturers to take the initiative in order to benefit from these new possibilities – if the control architecture is solely determined by the subsystem suppliers, EtherCAT will just be a faster, less complex and more flexible fieldbus system.

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