High Speed Industrial Ethernet for Semiconductor Equipment

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Abstract

A real time industrial Ethernet technology is shown, which overcomes the limitations of existing and upcoming solutions. It is shown that this technology named EtherCAT (Ethernet for Control Automation Technology) sets new standards for real-time performance since it communicates the data of 1000 distributed I/Os in 30 µs using standard twisted pair cable.

The system allows one to combine line, tree and star topology, works with and without switches and thus leads to significantly reduced infrastructure costs. Ethernet and internet technologies are made available down to the electronic terminal level. As the entire protocol is implemented in hardware, the system performance is independent of the slaves processing power and is suitable for masters that have little processing power available for field bus communication purposes.

It is shown that this Ethernet technology fulfils the requirements of next generation semiconductor manufacturing equipment whilst preserving existing standards and investments where appropriate.

EtherCAT is an open technology, standardized by IEC and ISO and supported by an international user and vendor organization. SEMI standardization has also been initiated (7/06).

Introduction

Semiconductor equipment controls is characterized by a large variety of different controllers, operating systems, communication networks and interfaces. All control solutions have in common that they have to provide for additional components.

There are two ways to integrate those: devices for which moderate communication performance is sufficient can be connected via fieldbus systems.

Devices that have more demanding communication requirements with the controller such as extremely short reaction times or maximum data throughput have to be connected via a parallel backplane bus system. Examples for such backplane bus devices are fieldbus interface cards, high-speed I/O or motion control cards.

For an increasing share of control applications Ethernet connectivity is demanded or at least desirable. Used for uplink purposes, this interface enables integration in plant wide networks and remote diagnosis capabilities. And as the Ethernet technology furthermore promises low costs, ease of use and good performance, Ethernet is currently being introduced at the fieldbus level too.

However, Ethernet was developed for moving large data units and due to the minimum frame length has a huge overhead when transporting only a few bytes of data, thus leading to poor bandwidth usage (Fig 1.). Therefore in spite of using Ethernet with 100 MBaud data rate, most industrial Ethernet approaches provide a fieldbus performance similar to the existing fieldbus systems. Thus they can only replace the fieldbus system, but not the backplane bus of a control system.

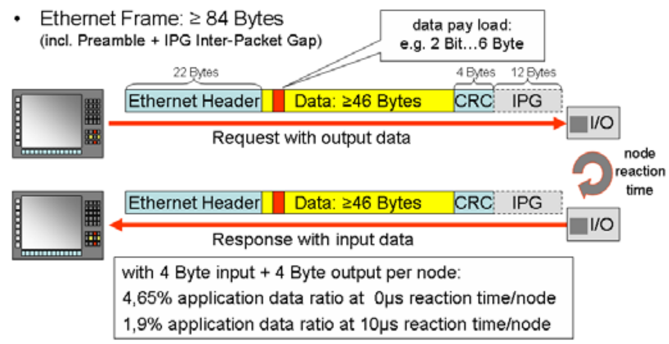

Figure 1: Poor bandwidth usage, poor performance

EtherCAT is an Ethernet technology that fully utilizes the bandwidth of full duplex 100 MBaud Ethernet. The resulting performance is outstanding and allows one to replace the backplane bus by EtherCAT as well. This leads to physically smaller controllers without expansion slots and with significantly smaller footprints, thus saving space and the related costs (Fig 2.)

Figure 2: Use of EtherCAT leads to smaller controllers

As EtherCAT master devices use standard Ethernet Medium Access Controllers (MACs) without extra communication processors, EtherCAT can be implemented on any equipment controller that provides an Ethernet interface, independently of the operating system or application environment. And as backplane bus devices can be placed externally, additional interfaces such as fieldbus scanner cards or motion control devices can be added without being limited by the number of available slots in the controller.

Introduction of EtherCAT technology does not necessarily mean changing the controller technology, and well established fieldbus systems can still be used in conjunction with EtherCAT.

In the following sections the EtherCAT Technology is explained in some detail.

Operating principle

From an Ethernet point of view, an EtherCAT bus segment is simply a single large Ethernet device. This

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"device" receives and sends Ethernet telegrams. However, the "device" does not contain an Ethernet controller with downstream microprocessor, but a large number of EtherCAT slaves. These process the incoming frames directly and extract the relevant user data, and/or they insert data and transfer the frame to the next EtherCAT slave. The last EtherCAT slave sends the fully processed frame back, so that it is returned by the first slave to the control as a kind of response telegram.

This procedure utilizes the fact that Ethernet deals separately with transfers in separate directions (Tx- and Rx-lines) and operates in full duplex mode: the transmitted frames are returned to the control by loop-back through the Rx-wire pair. Naturally, like for any other Ethernet device, direct communication without switch may be established, thereby creating a pure EtherCAT system in direct mode.

Telegram processing

Telegrams are processed directly "on the fly". While the frames (delayed by only a few bit times) are already passed on, the slave controller recognizes relevant commands and executes them accordingly. Processing is done within the hardware and is therefore independent of the response times of any microprocessors that may be connected.

Each device has an addressable memory of up to 64 kB that can be read or written, either consecutively or simultaneously. Several EtherCAT datagrams can be embedded within an Ethernet frame, each addressing individual devices and/or memory areas. The EtherCAT datagrams are transported in the data area of an Ethernet frame and can either be coded via a special Ethertype or via UDP/IP.

While the first variant with special Ethertype is limited to one Ethernet subnet, i.e. associated frames are not relayed by the routers, for control tasks this usually does not represent a constraint. The second variant via UDP/IP generates a slightly larger overhead (IP and UDP header), but for less time-critical applications it enables normal IP routing to be used. On the master side, already existing TCP/IP stacks can be used.

Each EtherCAT datagram consists of an EtherCAT header, the data area and a subsequent counter area (working counter), which is incremented by all EtherCAT devices that were addressed by the EtherCAT datagram and have exchanged associated data (Fig.3).

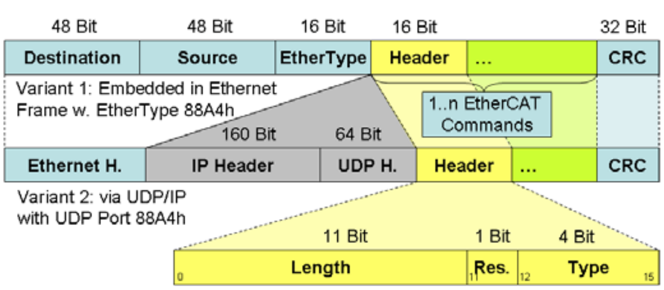

Figure 3: EtherCAT Telegram Structure

Protocol

Using the telegram structure described above, several EtherCAT devices can be addressed via a single Ethernet frame with several EtherCAT datagrams, which leads to a significant improvement of the usable data rate. However, for 2 bit input terminals with precisely 2 bit of user data, the overhead of a single EtherCAT datagram is still excessive.

Therefore the EtherCAT slave controller that enables individual address mapping for each device also supports bit-wise mapping. The two bits of the input device can be inserted individually anywhere within a logical address space. If an EtherCAT datagram is sent that reads or writes a certain process image area, instead of addressing a particular EtherCAT device, the 2 bit input terminal inserts its data at the right place within the data area (Fig 4).

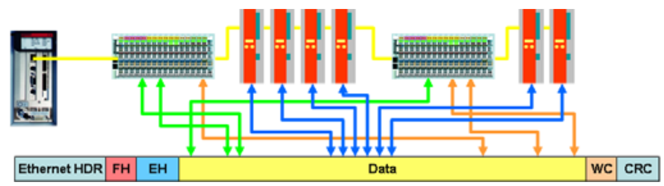

Figure 4: Devices map data directly in frame

All other devices that also detect an address match with the process image also insert their data, so that many devices can be addressed simultaneously with a single EtherCAT datagram. The master can assemble complete process images via a single EtherCAT datagram. Additional mapping is no longer required in the master, so that the process data can be assigned directly to the different control tasks (PLC, Motion Control, etc.). Each task can create its own process image and exchange it within its own timeframe. The physical order of the EtherCAT devices is completely arbitrary and is only relevant during the first initialization phase.

The logical address space is 4 GB. EtherCAT is therefore a type of serial backplane for automation systems that enables connection to distributed process data for both large and very small automation devices. Via a standard Ethernet controller and a standard Ethernet cable (CAT 5 or higher), practically any number of I/O channels without restrictions on the distribution can be connected to automation devices, which can be accessed with high bandwidth, minimum delay and near-optimum usable data rate. At the same time, devices such as fieldbus scanners can be connected as well, thus preserving existing devices and standards.

Performance

EtherCAT reaches new dimensions in network performance (Table 1). The complete protocol processing takes place within hardware and is thus independent of the run-time of protocol stacks, CPU performance or software implementation. The update time for 1000 distributed I/Os is only 30 µs. Up to 1486 bytes of process data can be exchanged with a single Ethernet frame - this is equivalent to almost 12000 digital inputs and outputs. The update of this

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data quantity only takes 300 µs, including the delay with the devices.

The communication with 100 servo axes can take place every 100 µs. At this rate, all axes are provided with set values and control data and report their actual position and status.

Table 1: EtherCAT Performance Overview

Process Data	Update Time
256 distributed digital I/O	11 µs = 0.01 ms
1000 distributed digital I/O	30 µs
200 analog I/O (16 bit)	50 µs equivalent to 20 kHz sampling rage
100 servo axis, each with 6 Byte Input + 6 Byte Output	100 µs
1 DeviceNet Scanner Process Image (1500 Bytes Input + 1500 Bytes Output Data)	150 µs

The extremely high performance of the EtherCAT technology enables control concepts that could not be realised with traditional fieldbus systems. With EtherCAT, a communication technology is available that matches the superior computing capacity of modern Industrial PCs. The bus system is no longer the "bottleneck" of the control concept. Distributed I/Os are recorded faster than with most local I/O interfaces.

EtherCAT instead of PCI

The central PC becomes smaller and more cost effective because additional slots are not needed for interface cards since the onboard Ethernet port can be used. With increasing miniaturisation of the PC-components, the physical size of Industrial PCs is increasingly determined by the number of required slots. The bandwidth of Fast Ethernet, together with the data width of the EtherCAT communication hardware (slave controllers) enables new directions: Interfaces that are conventionally located in the IPC are transferred to intelligent interface devices connected via EtherCAT (Figure 5).

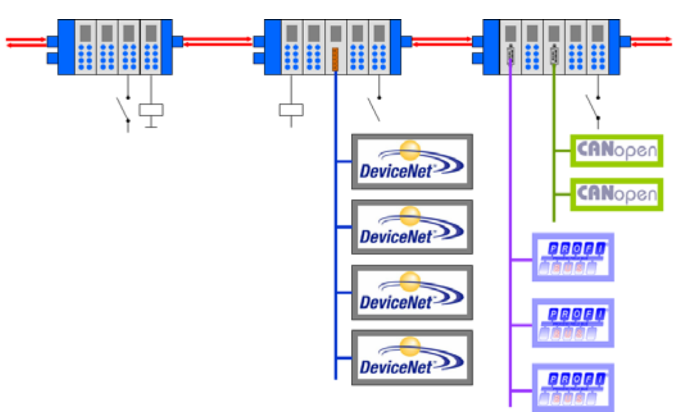

Figure 5: Decentralized fieldbus interfaces

Apart from the decentralised I/Os, axes and control units, complex systems such as fieldbus scanners, fast serial interfaces, gateways and other communication interfaces can be addressed. The central IPC becomes smaller and therefore more cost-effective, one Ethernet interface is sufficient for the complete communication with the periphery.

Distributed Clock

Accurate synchronisation is particularly important in cases where widely distributed processes require simultaneous actions. This may be the case, for example, in applications where several servo axes carry out coordinated movements simultaneously.

The most powerful approach for synchronisation is the accurate alignment of distributed clocks, as described in the IEEE 1588 standard [5]. In contrast to fully synchronous communication, where synchronisation 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, for each device the propagation delay to the master clock can be determined accurately. 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 then 1 microsecond is available. Whilst the clock synchronisation within one segment is done with a simplified protocol, external synchronisation can be provided by the IEEE 1588 protocol, thus enabling a plant wide time basis even with heterogeneous network infrastructure.

Physical layer

Since EtherCAT is fully compatible with Ethernet, all associated full duplex physical layers can be used, such as 100BASE-TX. EtherCAT transmissions often involve very short distances, for example between two EtherCAT terminals within the same terminal block, so that an additional physical layer based on LVDS transmission as specified in [3, 4] is used for such modular devices.

Since all transferred data consist of fully compatible Ethernet telegrams, the physical layer can be changed anywhere and any number of times. In a system consisting of different control cabinets and equipment modules, for example, for each unit the most cost-effective physical layer can be used. Within a modular device LVDS is sufficient; between separated modules fully isolated standard 100BASE-TX can be used for distances of up to 100 m. For even larger distances or extreme EMC loads, fiber optic technology can be implemented anywhere within the system.

The only prerequisite for the transmission medium is full duplex capability, since EtherCAT responds so quickly that usually the response is already sent back to the master, while the master is still sending the last bytes of its query.

Topology

The topology of a communication system is one of the crucial factors for the successful application in automation. The topology has significant influence on the cabling effort,

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diagnostic features, redundancy options and hot-plug-and-play features.

While the star topology commonly used for standard Ethernet (100BASE-TX) has advantages with regard to hot-plug-and-play, the cabling effort and switches required in distributed applications with many devices are not really acceptable.

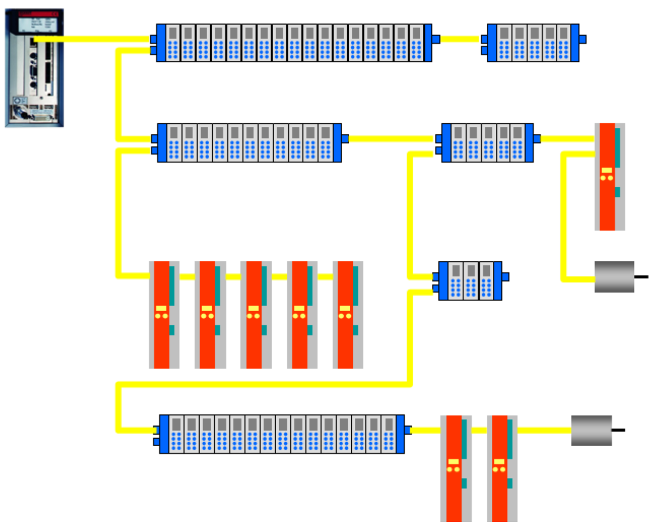

Figure 6: EtherCAT supports flexible tree topologies

In logic terms, in EtherCAT the slaves represent an open ring bus. At the open end, the master sends in frames, either directly or via standard Ethernet switches, and receives them at the other end after they have been processed. All frames are relayed from the first device to the next ones. The last device returns the frame back to the master. Since a normal Ethernet cable is bi-directional (separate Tx and Rx cables), and since all EtherCAT slaves can also transfer in the reverse direction, the result is a physical line.

Branches, which in principle are possible anywhere, can be used to build a flexible tree structure from the line structure (Figure 6). A tree structure enables very simple wiring; individual branches, for example, can branch into control cabinets or machine modules, while the main line runs from one module to the next. Hot Connect of network segments is supported as well as a ring structure for cable redundancy.

Diagnostic Features

For the operation of a distributed bus system, diagnostic options are no doubt just as significant as performance data, topology features or cabling effort. In this respect too, EtherCAT meets the expectations of a modern communication system. Unlike party line bus systems (e.g. Profibus or CAN based systems such as DeviceNet), in which all devices are connected to the same physical cable, and the signals are sent to all devices without being refreshed, Ethernet (at 100 MBaud or above) and naturally also EtherCAT uses pure point-to-point transfers. Faults or even sporadic weak points that are impossible to trace in party line systems, or only with special measurement arrangements, can be located accurately.

Breaks in the logical communication ring are located and closed automatically. Each device monitors the carrier signals both in the outgoing and in the return direction and can detect faults.

Error Detection

EtherCAT checks (via checksum) whether a telegram was transmitted correctly and was processed correctly by all addressed devices (using a working counter). The standard Ethernet checksum found at the end of the Ethernet frame is used for this purpose. Since one or several slaves modify the frame during the transfer, the checksum is recalculated for each slave. If a checksum error is detected, a status bit is set in the EtherCAT slave, and an interrupt to the master is triggered if necessary, so that a fault can be located precisely.

During a write operation, the slave inserts the addressed data in the designated data field, from where they are retrieved during reading as required. In both cases, the addressed slave increments a working counter positioned at the end of each EtherCAT command. Since the master knows how many slaves are addressed by the telegram, it can detect from the working counter whether all slaves have exchanged their data correctly.

Parameter and Process Data Handling

Fieldbusses have to meet different requirements in terms of the data transmission characteristics. Parameter data is transferred acyclically and in large quantities, whereby the timing requirements are relatively non-critical, and the transmission is usually triggered by the control. Diagnostic data is also transferred acyclically and event-driven, but the timing requirements are more demanding, and the transmission is usually triggered by a peripheral device.

Process data, on the other hand, are transferred cyclically with different cycle times. It is important that "dropped cycles" are avoided. The timing requirements are most stringent for process data communication. EtherCAT has different addressing options for different types of communication, optimized for the particular requirements.

Internode communication

Although EtherCAT uses a clear master/slave communication model, thereby ideally supporting hierarchical control technology, internode communication between EtherCAT devices can be created very easily. To this end, memory areas from the 4 GB logical address space are allocated for internode communication and cyclically exchanged by the master. The master alternately issues a read query and, in the next cycle, a write command for the respective data area. All devices that are configured accordingly insert their internode communication data or retrieve them during the next cycle. For the master, this data is transparent – it merely deals with the cyclic exchange.

Compared with party line bus systems, in which all devices are connected to the same communication medium, one cycle is 'wasted'. However, this is more than compensated for by the outstanding usable data rate and the

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associated short cycle times. The strategy described above also has the advantage, that the internode communication data is collected from several sources and then simultaneously arrives at all addressed destinations during the next cycle. At a cycle time of, for example, 100 µs, approximately 1000 bytes can be sent from almost any number of sources to the same number of destinations. It is also possible to transfer data from one slave device to a "downstream" slave device within the same communication cycle.

Ethernet over EtherCAT

In addition to the already described EtherCAT addressing mode for the communication with the EtherCAT devices, an Ethernet fieldbus is also expected to feature standard IP-based protocols such as TCP/IP, UDP/IP and all higher protocols based on these (HTTP, FTP, SNMP, etc.). Ideally, individual Ethernet frames should be transferred transparently, since this avoids restrictions with regard to the various protocols.

EtherCAT simply tunnels and re-assembles the Ethernet frames. This procedure does not restrict the achievable cycle time, since the fragments can be optimized according to the available bandwidth (EtherCAT instead of IP fragmentation). The acyclic Ethernet traffic does not affect the real time behavior of the network. By using a separate logical channel any EtherCAT device can participate in the normal Ethernet traffic. In an intelligent drive controller that exchanges process data with a cycle time of 100 µs, for example, an HTTP server can be integrated that features its own diagnostics interface in the form of web pages.

Another application for transferred Ethernet telegrams are the so called switchport terminals. These offer standard Ethernet ports with associated RJ45 sockets at any location within the EtherCAT system, through which any Ethernet device may be connected. For example, this may be a service computer that communicates directly with the equipment controller via SECS/GEM, queries the web page of an intelligent EtherCAT device, or simply routes it to the intranet or Internet via the controller. The EtherCAT master also features software-integrated switch functionality, which is responsible for the routing of the individual Ethernet telegrams from and to the EtherCAT devices and the IP stack of the host operating system. The switch functionality is identical with that of a standard layer 2 switch and responds to the Ethernet addresses used irrespective of the protocol (Fig. 7).

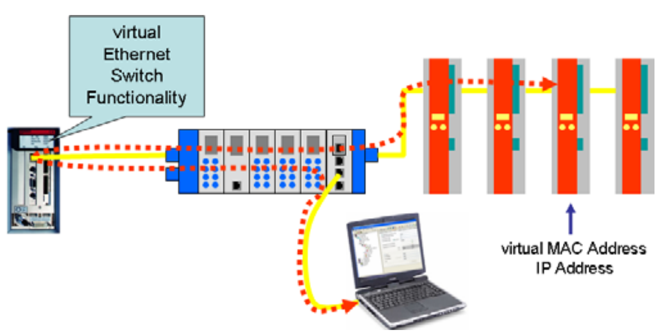

Figure 7: Ethernet over EtherCAT

Openness

The EtherCAT technology was initially developed by Beckhoff [2], a pioneer in PC based controls and well known fieldbus company. Beckhoff has taken every effort to ensure that the EtherCAT technology is fully open. The protocol tolerates other Ethernet-based services and protocols on the same physical network - usually even with minimum loss of performance. There is no restriction on the type of Ethernet device that can be connected within the EtherCAT segment via a switchport terminal.

The EtherCAT specs have been fully disclosed. Furthermore, EtherCAT already is an IEC Spec [6] and is part of several IEC and ISO communication standards [7..10]. SEMI standardization (E54) has been initiated in July 2006 with a due date of July 2007.

EtherCAT Technology Group

Everyone should be able to use and implement EtherCAT. The EtherCAT Technology Group (ETG) stands for this approach. The ETG is an international non-profit organization with more than 340 member companies from Europe, North America and Asia/Pacific (Fig. 8). It is a forum for end users from different industries, machine manufacturers and suppliers of powerful control technology, with the aim of supporting and promoting EtherCAT technology [1].

Member companies receive preferred access to specification drafts, specifications, white papers, tools, prototype evaluation products and initial batch products and get special support for evaluating, using or implementing the EtherCAT technology. The members are eligible to participate in working groups and gain influence on future enhancements of the EtherCAT technology specifications.

Figure 8: EtherCAT Technology Group Members as of June 2006

Large membership figures are nice, but not crucial. What really counts is the adoption rate of a new technology. As of April 2006, ETG member companies had acquired more than 200 development kits (¾ slave, ¼ master). At Hannover Fair (HMI) 06, 42 vendors already showed more than 80 different devices, among those 11 master implementations using 8 different operating systems (Fig. 9). There even are open

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source master implementations available. The ETG is a SEMI member and had a booth at SEMICON West 2006.

Figure 9: Choice of EtherCAT Devices at HMI 2006

Conclusions

In automation technology, there is currently a trend to use Ethernet also at the field level. Various approaches promise high bandwidth, low costs, simplified vertical integration, and utilization of standard components from the office sector and low configuration and diagnostic effort, and all that combined with the required real-time capability.

At closer inspection however, many of the arguments become weak or change into the opposite: The comparatively high bandwidth of 100 MBaud Ethernet is ruined if typical I/O nodes with few bytes of process data are used, each addressed by one frame. A device with four bytes per direction, for example, achieves a usable data rate of 3-4 percent. Costs too tend to argue against use in the field. Apart from the pure connection costs, another factor is the relatively high computing capacity required for processing of the telegrams in the slaves. The use of standard components usually reaches its limit when a certain degree of real-time capability is required. Furthermore, the typical switched star cabling is not ideal for use in the field. Even the configuration does not become easier: The allocation of the required IP addresses requires IT knowledge and tools and may lead to conflicts with the IT department, if the equipment has to be integrated in an IT environment. The 6 Byte MAC addresses tend to be a problem when devices have to be exchanged, as the new device cannot get the address of the old one and the new address has to be made known to the system, e.g. by configuring the DHCP server.

EtherCAT takes a different route and combines the advantages of fieldbus technology with the otherwise indisputable advantages of the Ethernet world. The available bandwidth is almost fully utilized, and the costs are reduced to a simple FPGA or ASIC connection in the EtherCAT device. Standard components are used where they are in fact standard - in the controller and not in the 2 bit I/O terminal. EtherCAT does not require IP addresses, and configuration is automatic – controlled by the master using simple algorithms. Simple vertical integration is nevertheless available. Devices requiring an IP address can have one and are then integrated fully transparently in the network, all internet technologies are available.

EtherCAT enables high-performance machine controls to be realized, capable to exchange many distributed signals with cycle times significantly below 100 µs. Moreover, the system is just as suitable for cost-effective control applications where cycle times three orders of magnitude larger are sufficient, e.g. in building automation with 100 ms. Any commercially available PC or any controller with an Ethernet port can be used as a master. EtherCAT therefore offers a unified, powerful communication basis for the entire automation sector. The same system technology can be used from “small” PLCs to high-performance CNC.

As EtherCAT replaces the fieldbus as well as the backplane bus, the controllers do not have to provide slots for enhancements any more. The control hardware shrinks whilst the expandability is increased. Furthermore, existing fieldbus systems can be integrated by means of decentralized scanner devices, also connected via EtherCAT. And as EtherCAT can easily be implemented on any operating system, the controller environment does not have to be changed completely in order to take advantage of this system.

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