Industry 4.0 Forum: PC-based Control Concepts as Core Technology for the Smart Factory
PC-based Control —
The technological foundation for Industry 4.0
The evolution of Industry 4.0

The purpose of Industry 4.0 is to make manufacturing more flexible, efficient and sustainable through communication and intelligence, thus increasing the competitiveness of German industry. One major component of this approach is control technology, which is still far from reaching its full potential. Improved communication methodologies and the rising convergence of information and automation technologies will deliver significant progress — something Beckhoff has always focused on with its PC-based control technology and fieldbus communication.

The convergence of information and automation technologies is at the core of this development, of which Beckhoff was the pioneer over 25 years ago with its PC-based control technology, which continues to provide the ideal control architecture for future concepts. As the core technology for Smart Factory concepts, PC-based control will be in focus in the Industry 4.0 forum. With the PC as the generally accepted technology platform in combination with Automation Device Specification (ADS), the EtherCAT Automation Protocol (EAP) and the OPC Unified Architecture (OPC UA), users have all the resources they need to implement the kinds of vertical and horizontal integration required by Industry 4.0.

In addition, TwinCAT 3 automation software provides the necessary modularity and object-orientation. Since TwinCAT 3 automation software is based on Microsoft Visual Studio®, users in the field of automation now have the IT world’s foremost software engineering tools at their disposal across the entire product life cycle.

With "Integrated Industry – Next Steps" as its motto, Hannover Messe 2014 signals that Industry 4.0 continues to be the main topic at the world’s leading industrial trade show. In the implementation of Industry 4.0, PC-based control technology from Beckhoff provides the ideal toolbox for these concepts. Even today, many users are integrating Beckhoff controllers into their production networks, letting them communicate with databases, performing remote maintenance over the Internet or requesting cloud-based services. Beckhoff will demonstrate these and other technologies, functions and services live. New products and advances will continue to support this development over the coming years.

We want to demonstrate at this year’s Hannover Messe that the open PC-based control technology makes it possible today to seamlessly integrate production systems and modules into existing or new systems so that they can communicate with each other as well as with higher-level production planning and control levels. Any changes in the job schedule or the current production run can thus have an immediate impact on the production flow. All of this already functions in practical applications. To fully implement Industry 4.0, however, additional research and development is still needed over the coming years.

The technology demonstration covers various sub-processes for a Smart Factory:
- consistent communication from the sensor to the cloud
- M2M communication via the “Internet of Things”
- new operating and diagnostic concepts in the form of web-based operating consoles and data glasses
- process reliability via integrated measurement technology and Condition Monitoring
- sustainable production with power monitoring and power management
- RFID as the basis for parts tracking and “intelligent products”
- integration of robotics and innovative drive technologies
- flexible and efficient production of lot sizes ranging from 1 to n through highly dynamic positioning with the XTS linear transport system
- integration of safety and security
- consistent engineering
- reduced commissioning times through real-time simulation
- remote production facility maintenance worldwide

We reserve the right to make technical changes.
Technology demonstration for a Smart Factory

- Smart Grid
- Smart Building
- Internet of Things/Services
- Cloud Computing
- Big Data
- ADS, OPC UA
- MES/ERP
- EAP, ADS, OPC UA
- Engineering
- PC Control
- Fieldbus
- Process
- EtherCAT
- Human Machine Interface (HMI)
- DVI/USB
- Cloud connectivity
- MES/ERP connectivity

Flexible transport system
RFID reader
Power Monitoring
Condition Monitoring
Drilling stations
Pick-and-place robot
Product transport

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The demonstration consists of two physically separate production systems — so-called smart factories — that communicate with one another over the Internet. The main job of one system (a pick-and-place XTS) is the intelligent sorting and transportation of products. The second system — the processing centre — simulates a customer-specific production process with two intelligent processing stations, a cross-process quality monitoring system, and a highly flexible handling and conveying system. At the start of the production process, a pick-and-place robot takes the workpiece to be processed from the warehouse and places it on the mover of the linear XTS (eXTended Transport System). A position sensor makes sure that the workpiece was successfully transferred. The XTS then moves the workpiece quickly and with a high degree of precision to the RFID reader and the processing stations, where it is machined according to customer specifications. The flexible conveyor systems, dynamic robotics and state-of-the-art identification system interact to permit the customer-specific production of lot sizes ranging from 1 to n.

The primary objective of the production network is to operate with exceptional resource efficiency, process reliability and availability. It collects data from all the systems involved (ranging from individual sensors to the cloud), analyses them on various system levels, and uses them to optimise the overall process. That way, the smart factory is able, for example, to analyse its total energy consumption including that of individual modules in the cloud in order to detect and reduce energy consumption peaks. At the same time, each production system monitors its own energy consumption and its status in order to detect wear-and-tear, contamination or power dips, and to proactively take countermeasures against increased energy consumption, unplanned system downtime or machining errors.

The basis for the intelligent, highly flexible and proactive control of automation networks is provided by a concept called Scientific Automation. Scientific Automation refers to the integration of engineering knowledge and scientific findings from many different fields of application into automation technology. The demo application presents, among other things, the integration of kinematic transformations to control the robots and the integration of sensor functions to collect and analyse process data directly in the controller.

For the efficient and anticipatory operation of smart factories, the ability of human beings to combine information about the production process and current system behaviour with planned and actual key production numbers, draw appropriate conclusions and take corresponding actions continues to be indispensable, however. The demonstration includes various human-machine interfaces that support the interaction between machine operators, maintenance staff, production schedulers and management and the production process. They provide information on demand, which reduces the effort required to procure specific information and coordinate activities with others. For remote diagnostics, maintenance and communication activities among the systems themselves and between systems and operators, cloud services may also be used. These are the first solutions on the path to the so-called Social Automation, i.e. they integrate new developments in information and communication technology into automation technology and thus bring them onto the shop floor.

Engineering workstations exemplify the efficient deployment of development tools in the areas of control technology, electrical engineering and closed-loop design in combination with software engineering tools from the IT world for the consistent design and commissioning of networked, distributed and intelligent production systems. Design paradigms such as object orientation, modularisation and clearly defined interfaces make freely configurable and flexible production systems possible. An integrated and multi-disciplinary design process, real-time simulation in the design phase and automatic code generation cut down on the number of errors and reduce engineering and commissioning times.

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The pick-and-place XTS and the processing stations are centrally controlled via a C6930 Industrial PC. The runtime environment is provided by TwinCAT 3. The Industrial PC communicates with higher-level control systems. The pick-and-place XTS and the processing systems communicate with each other via the cloud. Central control of the systems provides advantages in engineering, data management and diagnostics. All data is available for centralised analysis and optimisation, and no additional communication processes are required.

With large assembly lines, multiple centrally controlled assembly and processing systems can be combined into a single system if required. This is where distributed control approaches have their advantages. For example, such a solution simplifies the replacement of individual modules, because the central control components must only be adapted to the new work station. In addition, systems or machines on the shop floor usually are not operated as stand-alones, but rather networked — a trend that will accelerate significantly in connection with Industry 4.0. Accordingly, each machine is controlled locally, but integrated into the overall system or Industry 4.0 scenario. One of the key enablers for this approach is the implementation on the software side, which Beckhoff supports with modular programming via TwinCAT. Ultimately, it is irrelevant whether ten software modules run centralised on a single CPU or individually on ten different controllers. How the data traffic is executed between the modules — whether on a local PC or equally deterministically and fast via the EtherCAT Automation Protocol (EAP) — also doesn’t matter. PC Control makes it easy to implement either version depending on the application requirements at hand.
Horizontal and vertical communication

The pick-and-place XTS and the processing system communicate with each other via standard Internet protocols. The system components communicate with each other as well. Different communication technologies can be used in order to accommodate specific application requirements.

Networked Smart Factories

In an ‘Internet of Things’ scenario, both the pick-and-place XTS system and the processing systems are Internet users. They communicate openly with each other over the Internet and use cloud services – in this application, for an evaluation of their energy consumptions. The Beckhoff Industrial PCs in combination with Intel® processors and Ethernet interfaces, Windows operating systems and the TwinCAT 3 automation software supporting the Automation Device Specification (ADS) and OPC Unified Architecture (OPC UA) enable web connectivity of the pick-and-place XTS and the processing system, taking common Internet security measures into account.

Consistent communication from the sensor to the cloud

The cloud is where information about the job status, the energy consumption and the status of the pick-and-place XTS and the processing systems are stored, analysed and then made available to the user via modern human-machine interfaces. PC Control uses ADS, EAP and OPC UA to handle the communication from the sensor to the cloud.
- ADS is a message-based, routable transport layer within the TwinCAT software system. It allows for non-cyclical communication within the TwinCAT system and with other tools, such as visualisation systems.
- The real-time-capable EAP can transmit process data between the EtherCAT masters down to the microsecond range by employing a publisher-subscriber mechanism.
- OPC UA is a standardised, non-proprietary Ethernet and web-based communication standard that enables seamless integration into MES and ERP concepts.

One of the current trends is the ability to analyse the data in real time on its way to the cloud.

Communication with management-level systems: the MES/ERP interface

Via EAP, ADS and OPC UA, the process automation of the production systems is linked directly to higher-level management systems like manufacturing execution systems (MES) and enterprise resource planning (ERP) systems. The timing requirements are much less strict on this level, usually ranging from seconds to a few milliseconds. On the other hand, this kind of communication may have to comply with other requirements that arise from the complexity of the production environment and its degree of organisation, such as security, authentication, alarms, trends, historical data, service-based communication, and more.

High-performance communication from the field level to the control level

For the EtherCAT communication between field level and control level, as well as within each level, the Industrial PC is equipped with standard Ethernet interfaces. The Industrial PC (C6920), EtherCAT coupler and servo axes for controlling the pick-and-place robot are linked via Ethernet cables. TwinCAT automation software provides the corresponding software modules for communication.

Since the high performance of EtherCAT ensures a consistent data flow under real-time conditions, the communication system supports the production flow and does not impede it with system-related wait times. EtherCAT collects data quickly and in a highly deterministic manner – be it less complex devices like the position sensors or complex devices like the pick-and-place robot and the XTS. With no underlying bus, all players communicate directly with each other via EtherCAT components and can achieve response times of less than 100 microseconds. With this level of performance, a single PC-based controller is able to handle the control of the individual systems, even the complex kinematics of the pick-and-place robot and the highly dynamic XTS conveyor, in addition to the control of the overall system. For this purpose, the XTS leverages the high speed and bandwidth of EtherCAT in order to compute the motor model in the PC and generate traveling magnetic fields.

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Customer-specific production is based on the following principle:
Orders are entered manually or generated at random (when in automatic mode). Orders that cannot be processed because of missing resources are postponed. The processing system calls the orders automatically and dispatches them according to their priority. Manually entered orders take precedence.

When the order has been dispatched, the pick-and-place robot takes the respective workpiece and places it on the next available mover of the XTS. The mover transports the workpiece past the RFID reader to the processing stations and finally to the warehouse for shipping. After successful processing, the pick-and-place robot takes the workpiece and forwards it to the delivery warehouse and before that sometimes to a weighing station. Position sensors ensure the safe transfer of the workpiece from the pick-and-place robot to the mover and from the mover to the pick-and-place robot.

6 RFID reader

Each workpiece carries an RFID tag containing the individual processing data. The system reconciles the data with the order data of the mover and the processing stations and initiates the necessary processing steps. The RFID reader is connected via the EL6001 serial EtherCAT Bus to communicate directly with the controller (M2M communication over the Internet of Things) via an OPC UA interface.

7 Pick-and-place robot

The pick-and-place robot is responsible for handling and repositioning the workpieces. It grabs them with the help of an electromagnet and places them in the desired position. To accomplish this, its axes are positioned in a highly dynamic manner with Beckhoff AX5000 series drives and AM8000 series motors.

The motion behaviour of the robot is based on delta kinematics. Among other things, the Beckhoff TwinCAT Kinematic Transformation supplement includes a function block for controlling delta kinematics. It is configured and parameterised in the TwinCAT system and then executed together with PLC and motion control on the C6930 Industrial PC of the processing centre. No separate CPU is needed to control the robot. The “Flying Saw” and “Cam Plate” motion functions synchronise the pick-and-place robot with the XTS so that the workpieces can be properly picked up and placed. The robot is able to handle conveyor speeds of up to 7 meters per second and implement accelerations of up to 9 g. Despite these high speeds and accelerations, an integrated dynamic servo control ensures that all movements are executed with high precision.

8 Highly dynamic XTS linear transport system (eXtended Transport System)

The linear XTS transports, positions and buffers the workpieces. It consists of a motor module, a rail, several movers, and the control software. The motor is fully integrated into the controller together with the power electronics and the position measuring system. One or more “movers” (non-wired, movable carrier modules) can be moved along the processing system very quickly and dynamically at speeds of up to 4 meters per second. Each mover can perform individual travel manoeuvres. To accomplish this, a separate three-phase AC-equivalent travelling field that moves the movers is generated via a dynamic control of the individual coils of the motor modules along the path. To let the controller know where each mover is located, the integrated position measuring system delivers information about its absolute position.

TwinCAT provides for easy handling of the desired motions by mapping the movers as regular servo axes. As a result, the programmer can use proven motion control solutions (PTP, NC, CNC). With the “Flying Saw” and “Cam Plate” function blocks, the movers can be synchronised with the pick-and-place robot in such a way that the workpieces are transferred while traveling. TwinCAT also provides pre-configured and tested software function modules for typical XTS applications that only require the parameters to be set. For example, the distance to the adjacent mover is a parameter that can be modified as needed during runtime. To control the XTS in the processing centre, functional extensions for collision avoidance, centrifugal force limitation, dynamic buffer management and automatic build-up are used as well.

9 Flexible individual product transport

The XTS can control the movers individually and independently of each other. Accordingly, different travel manoeuvres can be executed simultaneously on the same XTS. The movers transport the workpieces from one station to the next and position them with a high degree of precision. The movers can travel at different speeds. On straight segments with no processing stations they travel fast to save time. They pass the RFID reader at reduced speed so that the RFID tag can be read correctly. If workpieces must be re-processed, they can also be moved backwards. At the processing system, empty movers accumulate before the warehouse and wait for the next order. If several movers are in the queue, a newly arriving mover will recognise this and automatically perform an optimised braking manoeuvre in accordance with the configured dynamic parameters – before it reaches the end of the queue. As soon as the first mover receives a new order and leaves the queue to synchronise the pick-up of the
workpiece with the pick-and-place robot, all movers in the queue travel forward according to the configured dynamic parameters. The mover reports that it has completed its travel only when it has reached the target position. Naturally, each mover can receive a new travel order at any time. The collision monitoring system is permanently active along the entire travel path and during all movements. If the stream of workpieces varies, they are first separated and then forwarded to the next processing station with constant speed and distance between them.

10 Processing stations: Drilling

The processing centre drills workpieces with different hole patterns. To do this, two drilling stations with different procedures are available. Station 1 drills small holes, while Station 2 drills large holes. Each drilling station has a drill spindle and a feed axis. The axes are controlled via the EL7211 servo motor terminal with integrated One Cable Technology (OCT). Many integrated monitoring features for parameters such as over- and undervoltage, overcurrent, terminal temperature, and motor load via the computation of the I²T model provide a maximum of operational safety. State-of-the-art power semiconductors minimise power loss and return power to the intermediate circuit during braking. The EL9576 EtherCAT terminal stabilises the supply voltage. Low internal impedance and a high level of resistance against pulse peaks provide good buffering characteristics in addition to a power supply device. In addition, the power consumption of the drilling stations is recorded with the EL4303 EtherCAT terminal, and the data is evaluated by the power monitoring system. A condition monitoring system that is integrated into the controller ensures the availability of the drilling equipment.

Intelligence raises process reliability, availability and resource efficiency

Process reliability, equipment availability, sustainable production and high-quality products are the overall goals of the Smart Factory network. On the process level, the system collects data and analyses the power consumption and the condition of the processing units and the quality of each workpiece in real time. This also enables real-time process adjustments. The data is evaluated across all systems by cloud services. The system indicates power consumption peaks across the entire production network and identifies potential maintenance requirements.

11 More energy efficiency through power monitoring

The power monitoring approach demonstrated at the Industry 4.0 Forum focuses on the power being used by the individual system components in order to identify the total power consumption as well as power peaks and power wasters. The power consumption data is collected via the EL3403 EtherCAT terminal, which also records any power peaks. Based on the effective values for voltage (U) and current (I), the EL3403 computes the effective power (P), the power consumption (W) and the efficiency factor (cos φ) so that different operating modes or alternative main usage times can be assessed after a single production cycle. The internal pre-processing system in the EL3403 provides the values in the process image without requiring a lot of processing power in the control-ler. Since they are written every 15 minutes to the terminal’s non-volatile memory, they are available even after a power loss. And since they are also transmitted via EtherCAT to the controller, they are available to higher-level systems for continuous power monitoring applications. With Beckhoff TwinCAT Scope software, users are able to interpret the data and draw conclusions regarding power peaks and components with increased power consumption. TwinCAT Scope is integrated into the user application and displays the consumption of voltage, current, effective power and energy consumption over time in the form of charts and tables in real time for both the overall system and individual systems. The user can select time units of one minute, one hour or one day.

12 Enhanced availability through condition monitoring

Quality shortfalls or even system downtime can have many causes. One of the more frequent ones are defective ball bearings in the gearing mechanisms. To recognise such defects, the drilling stations in the processing stations are equipped with a condition monitoring system. Since defective ball bearings can be identified via a vibration analysis, the bearings are equipped with vibration sensors, whose data is recorded via the EL3632 EtherCAT terminal. The signals are then analysed in the Industrial PC with function blocks from the TwinCAT Condition Monitoring Library. The vibrations are first converted to frequency range with the Fast Fourier transform algorithm. Next, statistical trend analyses indicate when and where a failure might occur. When ball bearings show signs of wear, they typically emit modulated shock pulses. In the lower frequency ranges, they are covered up by normal vibrations, making them hard to detect. A calculation of the amplitudes based on the theoretical Hilbert Transformation tool, makes it possible to consolidate these shock pulses over a wide frequency range, identify them, and assign them to the rotating or stationary bearing components. To exclude malfunctions and measurement signal outliers, statistical methods and data clusters such as the standard deviation and kurtosis are used to derive suitable decision criteria. TwinCAT Scope processes and analyses the measurements in a way that is easy to understand and integrates them directly into the user application display.
The Industry 4.0 concept also requires new, intuitive operating concepts that make it easier for humans to perform their everyday work and interact more effectively with intelligent machines.

The processing system and the pick-and-place XTS are operated via a built-in 24-inch multi-touch panel (CP2924). The panel’s high touch-point density provides for accurate and reliable operation that is jerk-free for even the smallest control movements with short response times. Operators can check the power consumption of the whole system or the status of each drilling station even while wearing thin work gloves. The panel also makes it easy to enter new orders via the user interface. In addition, the operator can use the panel to “fly” through the entire line and check all parameters or to take a closer look at details such as trouble messages by zooming in.

Wearable devices – i.e., computer systems that the users wear on their body – help to make the operator’s job even easier. In the Industry 4.0 Forum, Beckhoff presents a head-mounted display, or data glasses, using which the user can check the current power consumption of the processing station, the pick-and-place XTS or the entire production system by reading a QR code. The system will also display error messages in the user’s field of vision immediately after an error occurs. The user can even confirm the message and reset the machine status via the data glasses. For example, operators can use the device to “directly” monitor their machine or even take action to change or correct the machine status, without always having to be on-site. To make this possible, the glasses are integrated into the control technology via TwinCAT automation software and communicate with a cloud-based web server that provides information about the TwinCAT-controlled machine. With applications like these, the data glasses represent a foundational technology for the so-called Social Automation. Future advances may include the ability to call up support information online such as maintenance schedules, or to trouble-shoot problems by video-chatting live with a remote specialist.

Nearly every user has a mobile device such as a smartphone or tablet PC at his or her disposal. As with the data glasses, the user can also use a mobile computing device to view error messages and current information on the system availability, power consumption and order status after reading a QR code or entering a web address. Historical data is also available. Accessing the machine’s processes from a mobile device is also possible, but not being demonstrated at the Industry 4.0 Forum.
At the Industry 4.0 Forum, two developer workstations show the basic steps involved in realizing a consistent engineering process—from the idea of a networked production system to commissioning via the TwinCAT 3 automation platform. Since TwinCAT 3 can be integrated into Microsoft Visual Studio®, automation objects can also be programmed via the 3rd Edition of IEC 61131-3 and the C or C++ programming languages. The resulting objects (modules) can exchange data and call each other irrespective of the language in which they were written. By integrating MATLAB®/Simulink® into TwinCAT 3, users can also simulate dynamic systems and test the control program against these simulations. The workstations demonstrate these applications the processing system included in the demonstration. Applications from the fields of measurement technology and condition monitoring further illustrate the use of the TwinCAT Condition Monitoring Library and the integration of TwinCAT 3 Scope to collect, process and visualise data. The ability to transfer data from proprietary engineering tools sets the foundation for a consistent development process. The Beckhoff system uses the TwinCAT XCAD interface to import data from the EPlan E-CAD tool into the TwinCAT 3 automation platform. Further features being demonstrated at the development workstations are the integration of axes into the control program and the analysis of cycle times with the Gantt chart.

Intelligent systems with Scientific Automation

As part of the Industry 4.0 Forum Beckhoff presents the research project “ScAut” (Scientific Automation). With the aim of making technical systems more intelligent, the project focuses on the integration of engineering and scientific findings from diverse areas of applications into standard automation. ScAut is one of more than 45 innovation projects carried out within the technology network it’s OWL (Intelligent Technical Systems OstWestfalenLippe). In 2012, it’s OWL was announced a Leading-Edge Cluster in the high-tech strategy competition of the BMBF, the German Federal Ministry of Education and Research.

The key project ScAut aims to develop a scientific automation platform for the development and operation of intelligent machines and plants with the ability for self-optimisation. For the implementation of intelligent, reusable automation solutions Beckhoff provides software modules or intelligent Bus Terminals. Leveraging these innovations, production systems will be able to autonomously adapt their behaviour:

- intelligent technical systems anticipate wear, reduce emissions and pollution, optimise their energy efficiency and avoid manufacturing defects. Thus, production rejects, throughput times and harmful emissions can be reduced, and the tool service life and the sustainability of machines can be increased without a significant increase of the costs for automation technology.

The platform will be developed in cooperation with four pilot applications. The system manufacturers Hüttenehlscher Maschinenbau GmbH & Co. KG (Verl), IMA Klessmann GmbH timber processing systems (Lübbecke) and Schirmer Maschinen GmbH (Verl) and the kitchen manufacturer Nobilia-Werke J. Stickling GmbH & Co. KG (Verl) are involved in the cooperation. Requirements for the new automation solutions are defined, solutions are developed and tested jointly and validated in operation. Basic technological and scientific research required for the project is carried out in cooperation with the University of Paderborn.

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