DEMec - Dep. of Mechanical Engineering
SAIC- Automation, Instrumentation and Control Section
Master in Mechanical Engineering

Electromechanical Systems

1st Year– 2nd Semester
2025-2026

Support documents to TP classes

Multi-axis motion and control systems

Paulo Abreu

2026 Edition

Multi-axis motion and control systems

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2026

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Contents

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Motion and Control Systems

Motion and control systems for multi-axis systems

- Compatibility with multiple types of electric motors (DC, Steppers, Induction, Servomotors)
- Motion functions: torque, positioning, speed control, and synchronization
- Hardware and software solutions from multi vendors
- Industrial communications options
- Safety functions

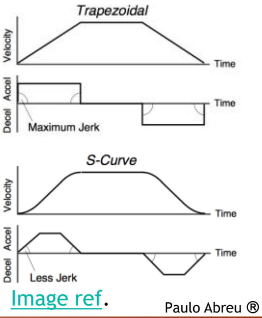
Foundations and Kinematics
Multi-Axis Trajectory Generation and Dynamics

Multi-axis synchronization requires precise control over individual axis profiles to minimize tracking errors and prevent mechanical resonance

Trapezoidal vs. S-Curve Profiles

The profile defines the kinematic setpoints sent to the velocity and position loops.

- **Trapezoidal Profile** (Piecewise Continuous Acceleration): Acceleration changes instantly, creating an unconstrained derivative of acceleration (infinite jerk $\dot{a} \rightarrow \infty$).This sudden change excites high-frequency mechanical resonances in the system structure
- **S-Curve Profile** (Bounded Jerk): Jerk ($j = \frac{d_a}{d_t}$) is explicitly bounded, creating a continuously differentiable acceleration profile. This minimizes structural vibration but increases trajectory computation complexity



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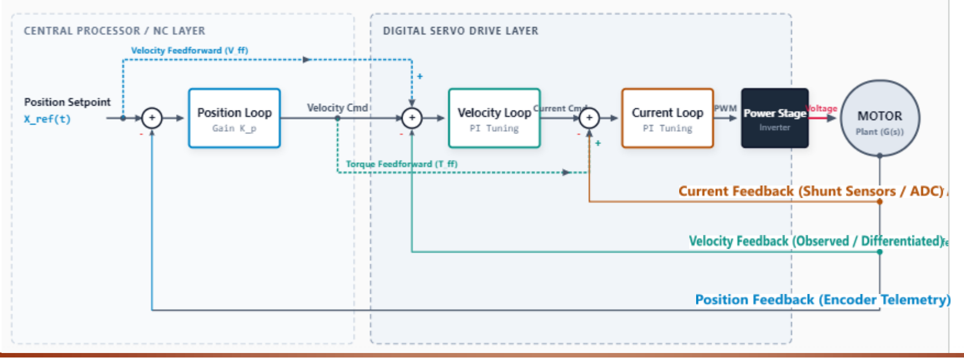
Foundations and Kinematics
Multi-Axis Trajectory Generation and Dynamics

Cascaded Multi-Axis Control Architecture

Industrial servo drives use a cascaded topology to isolate physical system limitations and ensure stable tracking performance. The structure embeds faster, inner loops within slower, outer loops



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Foundations and Kinematics
Kinematic Coordination and Multi-Axis Synchronization

Gearing, Camming, and Interpolation

In multi-axis industrial automation, moving individual machine axes independently is rarely sufficient. Most applications require high-precision coordination across multiple degrees of freedom. This coordination is handled using three primary kinematic techniques: electronic gearing, electronic camming, and multi-axis interpolation

Electronic Gearing

- Mathematical master-follower ratio
- Replaces physical shafts and gearboxes with nanosecond precision

Electronic Camming

- Non-linear mapping via spline tables
- Essential for complex cyclic movements in packaging

Path Interpolation

- Linear and circular coordination of multiple axes to trace a spatial vector (CNC/Robotics)

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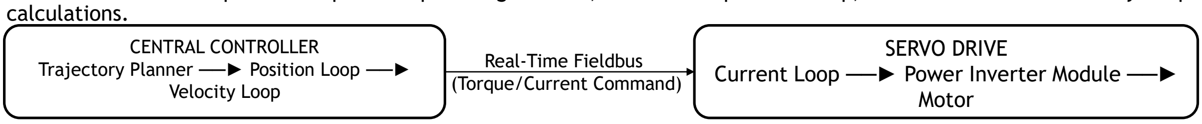
Distributed Loop Control Architectures

A key architectural design choice in multi-axis motion control is determining where to process the trajectory calculations and loop control blocks. This distribution impacts fieldbus network bandwidth, processing overhead, and axis synchronization capability. Modern systems use three primary structural approaches:

Topology A: Fully Centralized Loop Closure (PC/NC Based)

In this layout, the central controller (typically an Industrial PC or high-end dedicated controller) handles the entire control stack. It computes the position profile generator, closes the position loop, and executes the velocity loop calculations.



- **Data Transmission**: The controller transmits raw torque or current commands to the drive amplifier over a fast real-time fieldbus network
- **Network Impact**: This approach demands high network performance. The fieldbus must transfer high-frequency update frames with minimal transmission delay to prevent control loop instability
- **Vendor Implementation Examples**: This architecture is often used in Beckhoff TwinCAT configurations that use high-speed EtherCAT networks to close control loops directly on the central processor

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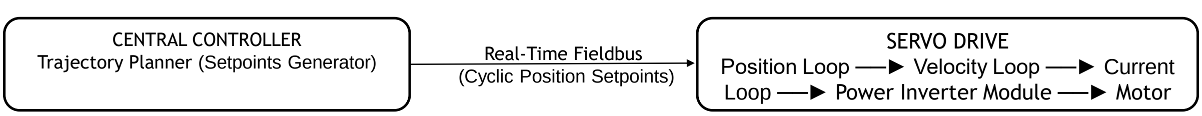
Distributed Loop Control Architectures

Topology B: Decentralized Loop Closure (Drive-Based Position Control)

This approach shifts responsibility for the feedback loops down to the individual drive modules. The master controller acts as a coordinator, generating raw position profiles and broadcasting path setpoints to the target devices



- **Data Transmission**: The network carries cyclic position commands rather than raw control effort variables
- **Network Impact**: This configuration significantly reduces processing load on the central controller and lowers fieldbus bandwidth requirements. Jitter on the network line is less critical because the drive handles the high-frequency loop dynamics locally
- **Vendor Implementation Examples**: This architecture is standard in systems like Siemens SIMOTION D, where intelligent SINAMICS hardware elements process cascaded feedback algorithms independently

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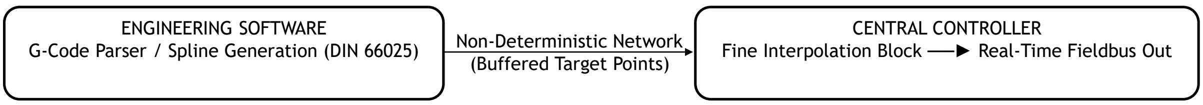
Distributed Loop Control Architectures

Topology C: Streaming Setpoint Control (CNC Command Processing)

Used primarily for complex tool path execution, this architecture splits computation across multiple system layers



- **Data Transmission**: The engineering platform parses path commands (such as G-code or complex splines) and streams buffered target coordinates to the motion controller
- **Network Impact**: The central controller performs fine interpolation calculations on these coordinates in real time. It converts the abstract path data into high-resolution micro-steps and streams them down to the physical drive loops
- **Vendor Implementation Examples**: This structural split is common in advanced machine automation systems, such as Omron PMAC units or Beckhoff CNC platforms

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System Topology: Central vs. Distributed

PC-Based Centralized

Trajectory generation and loop closure (Pos/Vel) occur on a high-performance central processor

- Native integration with higher-level ERP/MES systems
- Highly flexible for complex kinematics (Robotics, CNC)
- Requires ultra-fast fieldbus (e.g., EtherCAT)

Drive-Based Distributed

Intelligence is offloaded to the drive modules. The master only provides coarse setpoints

- Reduced computational load on the central PLC.
- Lower network bandwidth sensitivity
- Ideal for high-axis count standard synchronization

Industrial Networks and Real-Time Communications

Industrial networks must guarantee deterministic performance. Unlike standard enterprise IT networks, an automation network must ensure data frames reach their destination with precise timing and predictable delay. This consistency is essential for maintaining control loop stability and keeping multiple axes synchronized

Cycle Latency versus Jitter

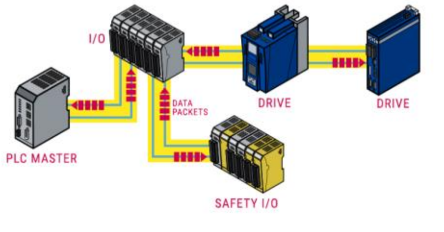
- **Cycle Latency (t_{cycle}):** The total time required for a network frame to traverse the entire control loop, including master processing, physical medium transmission, slave node updating, and the return path to the master
- **Network Jitter (δt):** The timing variance in frame arrival relative to a strict periodic schedule. In multi-axis motion systems, excessive jitter introduces phase lag into the feedback loops, degrades performance, and can cause unstable system behavior

Industrial Networks and Real-Time Communications
Deterministic Fieldbus Communications and Protocols

EtherCAT (Ethernet for Control Automation Technology)

EtherCAT achieves high data efficiency through a unique processing technique called "processing on the fly"

- **Frame Mechanics:** The master node sends a standard Ethernet frame that passes sequentially through all downstream slave devices. Each slave node reads its assigned output commands and inserts its sensor feedback directly into the moving data frame within nanoseconds, without buffering the entire packet.
- **Clock Synchronization**: EtherCAT uses a Distributed Clocks (DC) mechanism to keep devices synchronized. Nodes exchange propagation delay measurements to continuously align local timers. This technique corrects for network topology delays and keeps synchronization jitter between slave units under 1µs



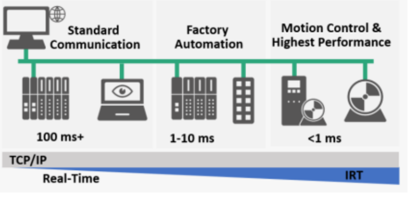
The functional principle of EtherCAT communication shows the movement of data packets from a PLC master to and from I/O blocks, VFDs/Drives, and Safety I/O.

Ref.

Industrial Networks and Real-Time Communications
Deterministic Fieldbus Communications and Protocols

PROFINET IRT (Isochronous Real-Time)

PROFINET IRT uses a scheduled transmission model based on Time-Division Multiple Access (TDMA) over standard Ethernet hardware



- **Frame Mechanics:** The communication cycle is split into two distinct, managed time windows: the Isochronous Phase and the Open Phase
- **Bandwidth Isolation**: The deterministic IRT phase reserves a dedicated time slot solely for time-critical motion setpoints and feedback frames. Non-deterministic traffic, such as standard IT data, web server access, or diagnostics, is blocked during this window and shifted to the open communication phase. This structure protects critical motion control loops from network interference caused by general data traffic

Industrial Networks and Real-Time Communications
Real-Time Networking Protocols

Feature	EtherCAT	PROFINET IRT	EtherNet/IP (CIP)
Mechanism	Processing on the Fly	Time-Division (TDMA)	Producer-Consumer
Sync Jitter	< 1 µs	< 1 µs	~ 100 µs
Topology	Line / Ring / Star	Point-to-Point / Star	Star

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Enterprise Integration, Safety and Ecosystems

Modern industrial engineering prioritizes software-configurable functional safety over simple, hardwired power disconnection circuits. Integrated safety protocols embed safe operating states directly into standard motion networks and drive hardware

Safety Over Fieldbus Protocols

- Platforms like TwinSAFE (Beckhoff) and AC500-S (ABB) use the "Black Channel" communication concept

  The “Black Channel” means that the **communication network is treated as unknown / untrusted / unsafe**, and **all safety is handled at the end devices**. Safety is ensured entirely by the safety protocol layer, not by the network. With Black Channel, Safety and standard data can share the same network.

- **Mechanism:** Safe data frames are encapsulated inside standard network packets (such as FailSafe over EtherCAT or PROFIsafe over PROFINET)
- **Validation:** The standard network components route this data without recognizing its safety status. The safety devices use unique frame identifiers, sequence counters, time-outs, and dedicated CRC signatures to independently validate the payload. If the network experiences data corruption, packet loss, or transmission delays, the safety hardware detects the fault and triggers a safe state shutdown automatically

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Hardware-Level Functional Safety Modes

Modern servo drives feature integrated, hardware-validated safety functions that protect operators while keeping machines running efficiently:

- **Safe Torque Off (STO):** The primary safety function. STO cuts power to the drive's output inverter transistors, preventing the motor from generating torque. The drive remains powered on and connected to the fieldbus network, which avoids the long startup times associated with a full system reboot.
- **Safe Stop 1 (SS1):** This mode controls deceleration during a stop request. When activated, the drive ramps the motor speed down along a managed deceleration profile. Once the motor reaches zero speed, the system automatically triggers the Safe Torque Off (STO) function to hold the axis safely in place.
- **Safely-Limited Speed (SLS):** This function monitors axis speed to ensure it stays below a specified safety threshold. If the motor exceeds this speed limit (for example, during manual maintenance or setup operations), the drive detects the over-speed condition and triggers an immediate safety shutdown to protect the operator.

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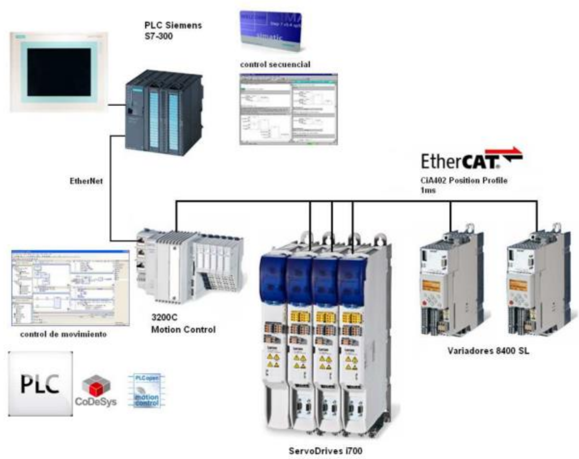
Lenze Motion and Control Systems

LENZE

- PLC based motion controllers
- Examples
  - c430, C520, C550, c250-S…



www.lenze.com

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Siemens Motion and Control Systems

Siemens SIMOTION and SINAMICS

A hybrid approach combining powerful PLC logic with distributed drive intelligence

- **SIMOTION D - Drive-based**
- **SIMOTION P - PC-based**
- **SIMOTION C - Controller-based**

- **Communication via PROFINET and PROFIBUS**
- **SINAMICS S120:** Modular multi-axis drive system for high dynamics
- **Platform:** TIA Portal

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Siemens Motion and Control Systems

Siemens
PC-based solution:

[SIMATIC PC-based Automation]

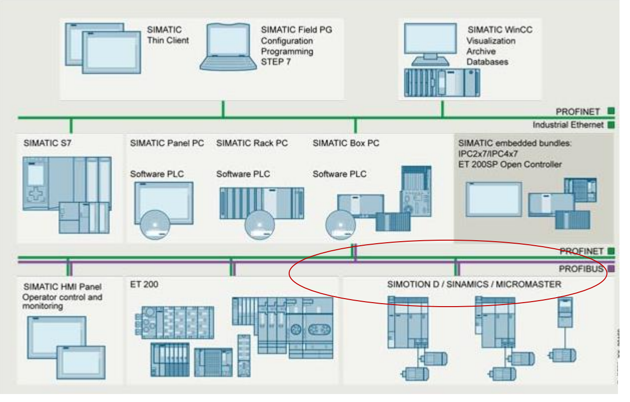

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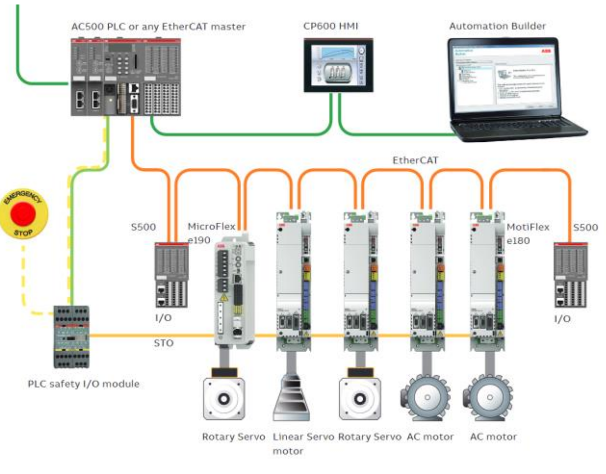
ABB Motion and Control Systems

ABB

- PLC based motion controller (AC500 series)
  - AC500
  - AC500-eCo
  - AC500-S safety PLC
  - AC500-XC
  - ABB PM595: Multi-core processing for up to 100 axes
- Automation builder software

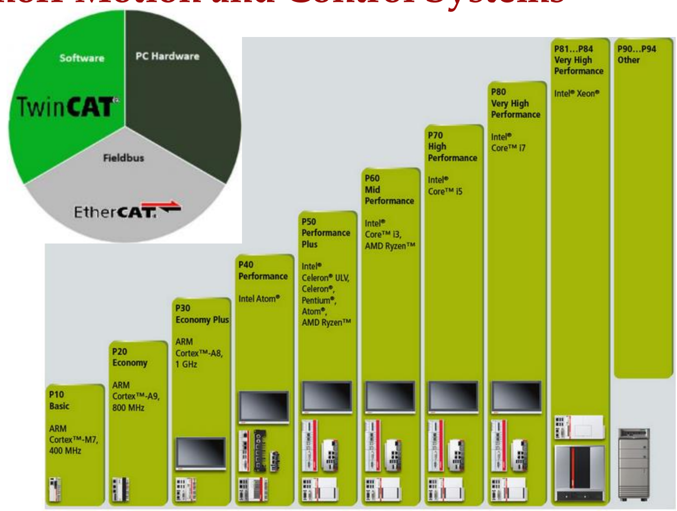
Reference document:
Abb PCL Automation, Automation Builder AC500



Beckhoff Motion and Control Systems

Beckhoff
PC-based control technology

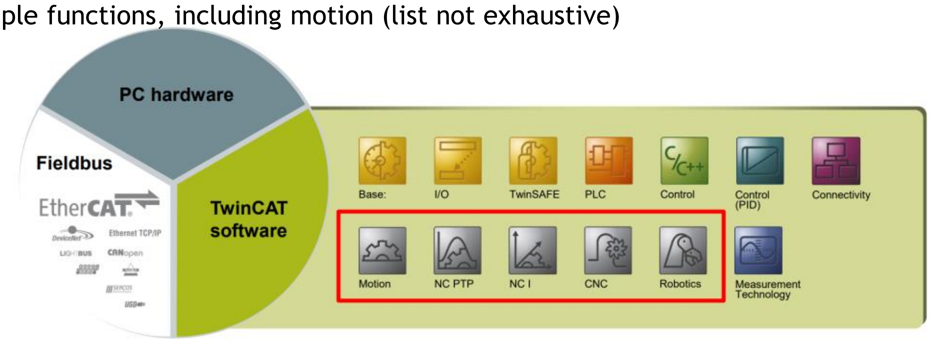
- Industrial PC and Embedded PCs
- Software: **TwinCAT 3** Architecture
  TwinCAT3: The "The One Tool" approach. Merging PLC, NC, CNC, and Robotics into a single environment
- Safety: TwinSAFE integrated functional safety
- Hardware solutions mapped to Software functions



Beckhoff Motion and Control Systems

Beckhoff software: TwinCAT3

- Multiple functions, including motion (list not exhaustive)



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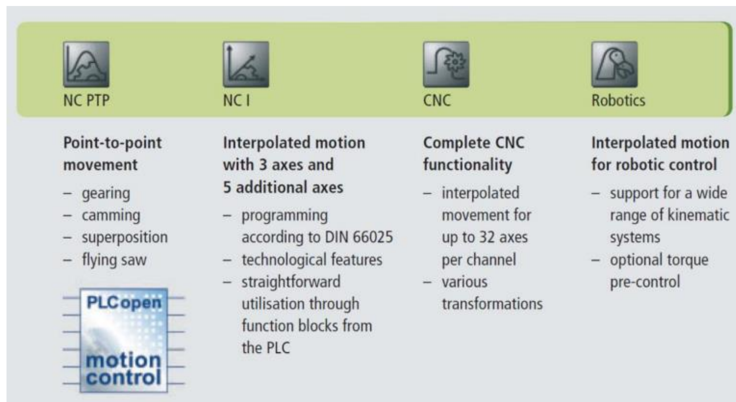
Motion and Control Systems

Beckhoff software: TwinCAT3

- Motion functions
  (list not exhaustive)



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Beckhoff Motion and Control Systems

Drives from Beckhoff

- Servo drive
- Distributed servo drives
- Rotary servomotors
- Linear servomotors
- Planetary gears
- Transport systems
- Compact drive technology
- ATRO: Automation Technology for Robotics

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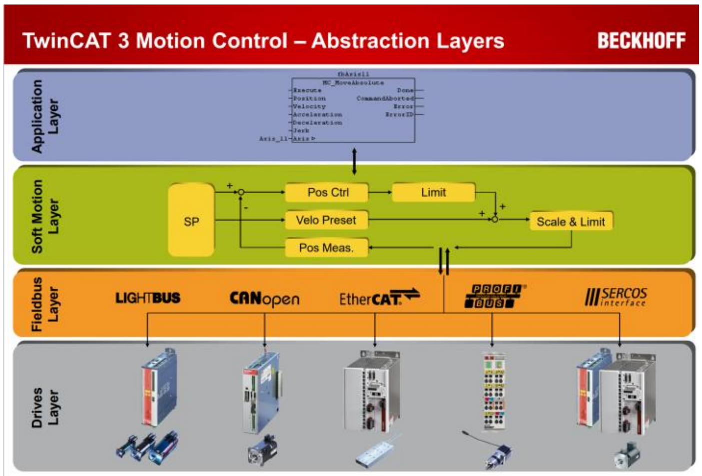
Beckhoff Motion and Control Systems



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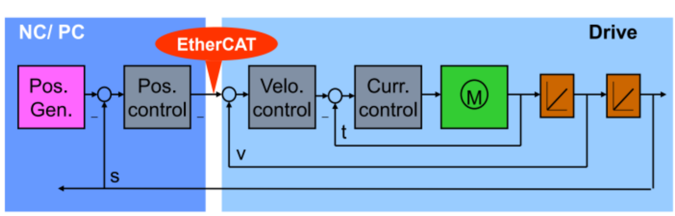
Beckhoff Motion and Control Systems

TwinCAT Motion Control – Control cycles

BECKHOFF

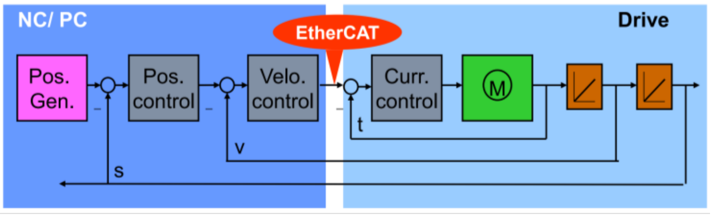
- Often used in the passed and in special application
- Position control loop closed in the PC
- Possible with fast EtherCAT fieldbus



Beckhoff Motion and Control Systems

TwinCAT Motion Control – Control cycles BECKHOFF

- For special cases – Velocity Control loop closed on PC
- Only Current Control loop closed in drive
- Only possible with
  - Fast control cycles on the PC
  - Deterministic realtime on the PC
  - Fast fieldbus: EtherCAT



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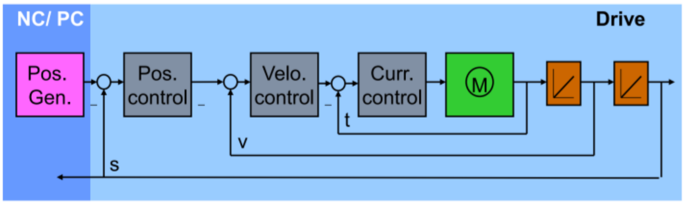
Beckhoff Motion and Control Systems

TwinCAT Motion Control – Control cycles BECKHOFF

- Most used configuration
- Position Control loop closed on the drive
- Only setpoint generation on the PC in TwinCAT



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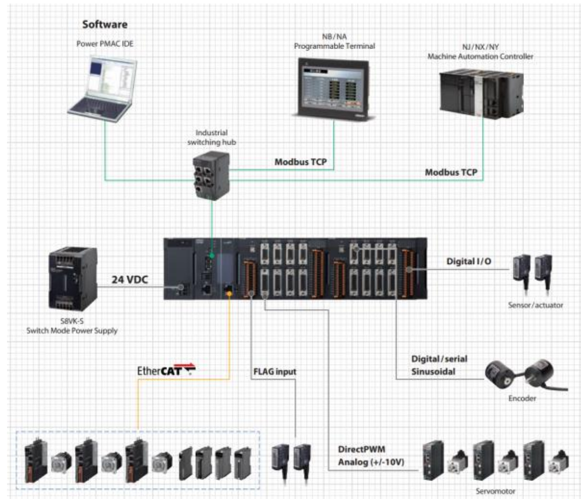
OMRON Motion and Control Systems

OMRON

Motion controllers

- PLC based (ex NC ethercat)
- CNC functionality (ex. NY PMAC)
- Machine controller (ex. NX7 , NJ5

- Software Sysmac Studio



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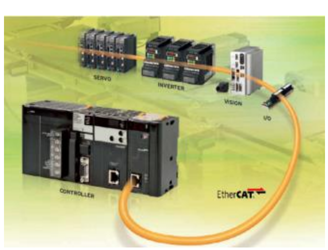
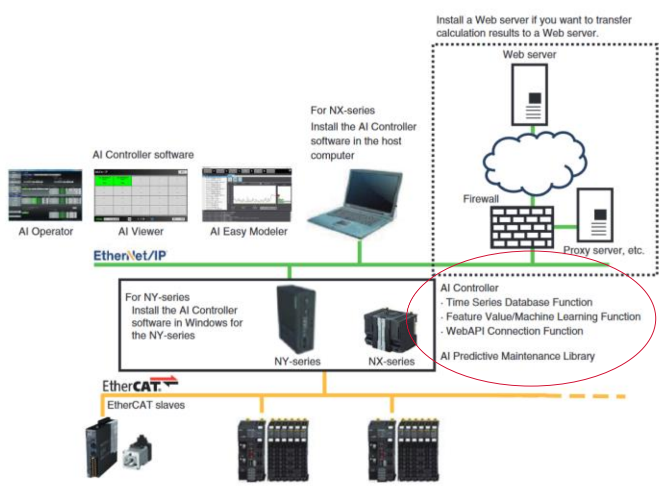
OMRON Motion and Control Systems

Motion Controller NX7

- The industry leader in cycle times (125 µs)
- Advanced PLC/Machine Controller: PLC-based architecture with PC like capabilities, with real-time industrial control





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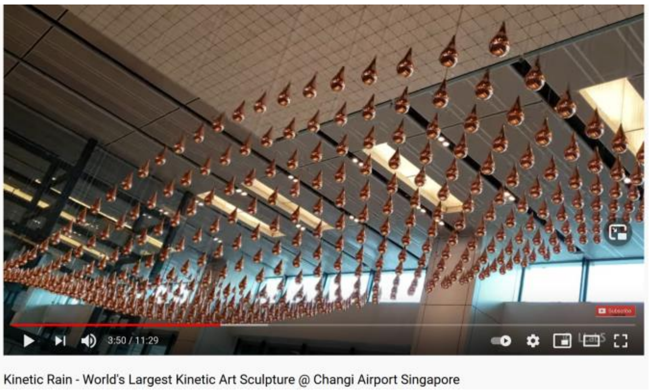
Gap Analysis and Vendor Architecture Mapping

Provider	Central Engineering Platform	Real-Time Fieldbus Network	Central Motion Controller Line	Dynamic Drive Families	Supported Electric Motor Tech
Lenze SE	PLC Designer (CODESYS Based)	EtherCAT, CANopen	**PLC-based** 3200 C, c750, c550	i700 Multi-Axis, Servo Inverter i950	MCS Synchronous Servos, m850 Asynchronous
Siemens AG	TIA Portal	PROFINET IRT / PROFIBUS	**PLC-based and Drive-based**	SINAMICS S120 Modular System, V90	Synchronous Servo, IM, Linear Motors
ABB Group	Automation Builder software	EtherCAT, PROFINET, Modbus TCP	**PLC-based**	MotiFlex e180, MicroFlex e190	BSM Servo Series, IM, Permanent Magnet
Omron Corporation	Sysmac Studio	EtherCAT	**PLC-based (NC4) Machine Automation Controller** (NX7)	1S Series Servos, G5 Series	AC Rotary Servos, Direct-Drive Linear Motors
Beckhoff Automation	TwinCAT 3	EtherCAT (Native Master)	**PC-based** (C-Series Industrial PCs)	AX8000 Multi-Axis, AX5000, EL72xx Terminals	AC Servos, Linear Synchronous, Stepper, BLDC

Case Study: Kinetic Rain

Engineering precision at scale

- 1,216 synchronized servomotors moving at 1.5 m/s with 0.25 mm accuracy
- Managed by **Beckhoff TwinCAT** and **seven** C6525 **Industrial PCs**; Servo terminals EL7201; servomotors AM3121 with holding brake
- Software: TwinCAT NC PTP; TwinCAT NC Camming
- Network cycle time of 580 μs
- Master IPC execution rate of 1.0 ms



Kinetic Rain - World's Largest Kinetic Art Sculpture @ Changi Airport Singapore

https://youtu.be/lB8ZxoaMdHg?t=26

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Case Study: Kinetic Rain Quantitative Analysis (I)

To guarantee system stability, the communication network must operate within a strict timing budget.

The total network cycle time (t_{cycle}) required for a single master IPC managing a subset of N = 174 axes using the following formula

$$t_{cycle} \geq t_{master\_proc} + t_{frame\_trans} + N \cdot t_{node\_delay} + t_{software\_jitter}$$

Where

t_{master_proc} = 125 μs (Time required for the IPC to execute PLC logic and compute motion trajectory profiles)

t_{node_delay} = 1.2 μs (Internal signal delay introduced as the network frame passes through each physical drive terminal)

$t_{software\_jitter}$ = 15 μs (Worst-case operational timing variance of the real-time software operating system)

The frame transmission time (t_{frame_trans}) over a 100 Mbps Ethernet network depends on the total packet size. For 174 axes, where each axis exchanges 8 bytes of command data and 8 bytes of feedback data within a standard Ethernet frame structure, the total packet size is roughly 2900 bytes. This yields:

$$t_{frame\_trans} = \frac{2900\ bytes \times 8\ bits/byte}{100 \times 10^6\ bits/sec} = 232\ \mu s$$

Case Study: Kinetic Rain Quantitative Analysis (II)

Calculating the minimum required cycle time gives:

$$\boldsymbol{t_{cycle} \geq 125\ \mu s + 232\ \mu s + (174\ \times 1,2\ \mu s)\ + 15\ \mu s}$$

$$\boldsymbol{t_{cycle} \geq 125\ \mu s + 232\ \mu s + 208,8\ + 15\ \mu s = 580,8\ \mu s}$$

This proof confirms that setting the network master execution rate to 1.0 ms provides a safe performance margin. This rate accommodates the network data transfer times and provides a safety buffer, ensuring reliable, deterministic multi-axis synchronization without network overload

Note that while standard industrial applications typically operate at cycle times between 250 μs *and* 1.0 ms, EtherCAT is fundamentally capable of go as low as 12.5 μs or 50 μs, due to its unique "processing on the fly" architecture. Achieving these ultra-low cycle times requires optimizing several strict physical and computational constraints. The limiting factor is rarely the network itself; it is usually the Master IPC's ability to calculate the motion equations and update the process image within that tiny window. To run a 50 μs, the master controller must read the inputs, execute the PLC/motion control loop, and prepare the next output frame in less than 35 μs $ to allow a safety buffer for jitter.

Conclusions

- **Vendor-Agnostic Control Systems:** similar control systems available from different vendors
- **Network-Based Solutions:** extensive use of EtherCAT for industrial networking
- **Standardized Communications:** implementation of standard communication protocols
- **Scalable Solutions:** flexible and scalable solutions to meet varying demands
- **Integrated Safety:** built-in safety functions for enhanced protection
- **Motor Compatibility:** compatibility with various motor technologies, including DC, stepper, induction, and servo motors
- **Software Tools:** advanced software tools for configuration and programming

Future prospects in electromechanical drives

- **Ongoing Development:** electromechanical drives are continuously evolving, with electronics playing a pivotal role, which is crucial for achieving higher efficiency, enhanced reliability, and greater power density
- **Energy Efficiency**: emphasis on enhancing energy efficiency at both the motor and controller levels
- **Technological Replacement**: transitioning from other drive technologies to more energy-efficient alternatives
- **Customization and Flexibility**: development of more adaptable and customizable drive systems to meet specific industry needs, along with robust software support
- **Digitization**: integrating network solutions for sensing, control, and predictive maintenance
- **Industry Integration**: aligning with Industry 4.0 and Industry 5.0 standards, incorporating IoT technologies

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