Machine Tool Controller Design

Joe, Chien-Yi Lee
CNC Controller System

- FAGOR 8070

System configuration

1. Numerical Control (CNC)
2. Sercos digital interface
3. Axis motors
4. Spindle motors
5. Feedback Systems
6. Tool magazine
7. Kinematics management
8. Ethernet
9. Simulator on PC
10. Distributed inputs and outputs
Controller System Architecture
Controller Hardware Design

一、Hardware Classification

1. Printed-circuit Board
   1. Large PCB
   2. Module

2. Microprocessor Number
   1. Single
   2. Multi

3. Hardware Manufacturing
   1. Dedicated
   2. Universal

4. Openness
   1. Closed
   2. PC Embedded NC
   3. NC Embedded PC
   4. Pure-soft Open CNC
Printed-circuit Board Type

1. Large PCB
   ◆ **Configuration:** main PCB, position control board, PLC board, graphic control board and power unit.
   ◆ **Feature:** Big circuit board for main board slotted by small circuit boards for other boards.
   ◆ **Representative:** FANUC 6MB series

2. Module
   ◆ **Function Module:** CPU, extended memory, position control, PLC board graphic and communication boards.
   ◆ **Communication Interface:** industry standard architecture bus (PCI, STD Bus)
   ◆ **Representative:** FANUC 15 series
Microprocessor Number

1. Single
   - **Single CPU**: centralized control and management of the entire system’s resources

2. Multi
   - **Master-slave**: master CPU for host management, slave CPU for client motion control
   - **Distributed**: exchange information and share resources by external communication link
   - **Multi-master**: common bus, shared memory
Multi Master Microprocessors

- **Feature:**
  - **Configuration:** two or more CPUs and their function modules.
  - **Handshake Mechanism:** common bus arbiter for solving priority and shared memory for exchanging information between multi-master CPUs

- **Function Module:**
  - **CNC Management:** CNC device management, such as initialization, interrupt management, and system software/hardware diagnosis
  - **CNC Interpolation:** pretreatment interpolation and real-time interpolation calculation
  - **Position Control:** motion control and position/velocity control
  - **PLC(PMC):** single logic processing for NC file command(S、M、T), operation panel control and limit switch on machine
  - **Input/Output and Display:** display for NC file, path, parameter and operation I/O
  - **Memory:** Data transfer for NC file and data storage between function modules.
Hardware Manufacturing

1. Dedicated
   - Feature: closed architecture that designed and manufactured by manufacturer, with advantages of high reliability, compact and dedicated
   - Representative: FANUC, SIEMENS

2. Universal
   - Feature: IPC as a hardware platform with dedicated control card and CNC control software, with advantages of high openness and good maintenance
   - Representative: Power Automation PA8000
Openness

1. Closed
   - Feature: user cannot add, change and maintain any function
   - Representative: FANUC 0, MITSUBISHIM 50, SIEMENS 810

2. PC Embedded NC
   - Feature: PC installed in CNC, with certain openness but system kernel modified is allowed
   - Representative: FANUC 18i/16i, SIEMENS 840D, NUM 1060

3. NC Embedded PC
   - Feature: composition of motion control card and PC, motion control card is used for CNC system and usually a high speed DSP is used as CPU
   - Representative: American Delta Tau company PMAC CNC system based on PMAC multi-axis motion control card, Japan MAZAK company MAZATROL 640 CNC system based on Mitsubishi Electric’s MELDAS MAGIC 64

4. Pure-soft Open CNC
   - Feature: RTLinux software development platform as a pure software CNC system
   - Representative: American MDSI company Open CNC, German PA company PA8000
PC Embedded CNC

PC installed inside CNC, bus connection between PC and CNC
NC Embedded PC

Non real-time process for system monitor management, fault diagnosis, interface display and interpreter.

Real-time process for interpolation calculation, tool compensation, position control and velocity control.
Universal Controller

- NC Kernel and Motion Control Card
Universal Controller

IPC

HMI,
OS: Windows

DSP

RS232
COM2

Multi-axis
Mechanism
CNC Data Processing Chain

1. Feed Systems
2. Linear Optical Encoder
3. Drives

CAM → CAD → NC Files → CNC Motion Controller → Interpolator → Servo Controller → PLC → Encoder
Control Process Design

- **Control Classification**
  1. **NC Control**: Numerical control for each axis coordinate
  2. **Auxiliary Control**: Sequence control for each responder action

- **Control Flow**
  1. Control Command, Parameters, Machining Data → Input Unit → CNC Storage Unit
  2. NC File Opened → Blocks Interpretation

![Diagram of CNC process design](image)
Control Process Design

- **Low Speed Auxiliary Information:**
  Output and process by PLC to realize auxiliary control
  1. **Auxiliary Function (M):** Spindle start/stop, coolant on/off, tool change...
  2. **Spindle Speed Function (S):** Spindle speed controlled
  3. **Tool Function (T):** Tool selection

- **High Speed Auxiliary Information:**
  Preprocess, interpolation and position control; simultaneously moving coordinate axes
  1. **Tool Compensation Process:** Part trajectory conver to tool center trajectory.
  2. **Feedrate Process:** Component velocity calculation and speed limit process.
Software System Design

- Software Classification

  1. CNC Device Operating Characteristics

    - 1. Real-time:
      - Strong real-time
      - Weak real-time

    - Periodic: Interpolation, motion control
    - Sudden: Emergency stop, alarm fault
    - Display: Trajectory, coordinate
    - Editor: Parameter, NC file

  - 2. Parallel Processing: Display, machining, I/O processing, troubleshooting

  - 3. Multi Processing

    - Control: Interpreter, tool compensation, path planning, motion control
    - Management: Input, I/O processing, display, diagnosis
Software System Design

- Software Classification

3. CNC Software Architecture
Tool Compensation

Compensation Kind

- Tool radius compensation: Cutter radius compensation for machining centers, tool nose radius compensation for turning centers
  - G40 (Cancel tool radius comp. G41 and G42)
  - G41 (Left tool radius compensation)
  - G42 (Right tool radius compensation)

- Tool length compensation: Adjust for differences in length between different tools
  - G43 (Tool length compensation plus)
  - G44 (Tool length compensation minus)
  - G49 (Cancel tool length comp. G43 and G44)

- Tool center offset compensation
Tool Length Compensation

- **Tool length compensation**

  - **G43**: tool length compensation in a positive direction
    \[ Z_{Act} = Z_{Cmd} + (Hxx) \]
  
  - **G44**: tool length compensation in a negative direction
    \[ Z_{Act} = Z_{Cmd} - (Hxx) \]

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Feature

NC Files:
- Lots of small line segments (CAM software) \( \Rightarrow \) curves \( \Rightarrow \) surfaces
- Effect of surface accuracy

1. CNC system delay
   - For high speed machining, low workpiece precision from servo delay caused by deviation between command and actual trajectory
2. CAM system output distortion

- Un-smoothing machining velocity of adjacent trajectories caused by irregular small line segments of adjacent paths.
- Tiny segment deviation, retrograde, ‘S’ mark
- Unsmooth surface of surface blemishes caused by servo delay.

Feature

Inconsistent path lengths or angles

Irregular corner

Path A
Path B
Path C
Path D
Precision Motion Command

- Coordinate movement for desired motion Axes
- Generation and interpolation
- **Interpolator**: trajectory planning
  - Continuous machining path converted to coordinate movement
- Output approximate coordinate movement every fixed time interval

![Diagram showing coordinate movement and motor rotation amount](image)

The target trajectory is assumed to be piecewise linear with some...
Interpolation

Feature of CNC Motion

Move in pulses
- Tool’s basic motion unit (BMU): Pulse
- Tool’s displacement magnitude along each coordinate direction: integer multiple of pulses.
- Machine Tool’s motion space: a discretized grid-area which a mesh size represents a pulse; tool only can be moved a grid node location.

Tiny linear segments to be machined
- Tool is moved to approximate the original curves or surfaces by a series of broken line;

NC Programming

G00 for Rapid Positioning
- Tool is moved along the shortest route to programmed X,Y,Z position

G01 for Linear interpolation
- Tool is moved along a line

G02 for Circular Interpolation Clockwise
- Tool is moved along an arc from the starting point to an end point

G03 for Circular Interpolation Counterclockwise
Interpolation

◆ Classification

☐ Hardware interpolation
  • High-speed algorithm but lack of flexibility, difficulty with adaptations and modifications
  • Early NC system: hardware interpolator consists of digital logic circuit
  • It is used for fine interpolation

☐ Software interpolation
  • Low-speed algorithm but high flexibility, ease with adaptations and modifications
  • CNC system: interpolation by pure software or software/hardware combination
  • It is used for rough interpolation.

◆ CNC’s Common Interpolation
  • Basic interpolation: linear, circular
  • Parametric interpolation: helical, parabolic, cubic…
1. Deviation Judgment: According to deviation symbol to determine positional deviation between tool’s current position and part contour.

2. Coordinate Feed: According to deviation judgment to control corresponding coordinate axis to move one step for approaching workpiece.

3. Deviation Calculation: After moving one step, recalculate new positional deviation for new tool’s position.

4. End Discrimination: 若 the end point is reached, stop interpolating; else, return step 1.
Point by Point Comparison

- **Linear Interpolation:** Deviation value $F_i$ is defined as the distance between the moving point and contouring $OE$

  1. Deviation $F_i = X_eY_i - X_iY_e$
  2. When $F_i \geq 0$, the moving point is over the straight line $\rightarrow$ moves one step along $+X$ direction;
  3. When $F_i < 0$, the moving point is below the straight line $\rightarrow$ moves one step along $+Y$ direction.

- **Circular Interpolation CCW:** Deviation value $F_i$ is defined as the difference between the moving point $N$ and arc radius $R$

  1. Deviation $F_i = X_i^2 + Y_i^2 - R^2$
  2. When $F_i \geq 0$, the moving point is outside the arc $\rightarrow$ moves one step along $-X$ direction;
  3. When $F_i < 0$, the moving point is inside the arc $\rightarrow$ moves one step along $+Y$ direction.
Extended DDA Interpolation

Feature

- Digital Differential Analyzer (DDA)
  - solves equations by numerical methods
  - a kind of increment algorithm
  - the value of x, y and z in next step will be figured out after x, y and z in previous step adds a small increment simultaneously and respectively.
  - high precision machining but simple algorithm
  - calculation of tool’s displacement along with coordinates to make tool is moved along the machining trajectory.
  - computing speed fast
  - the distribution of the controller pulse overflow is more uniform
  - easy to implement multi-axis moving simultaneously and complex multi-axis independent variable space curve interpolation
  - the most commonly used in numerical contouring control system
Extended DDA Interpolation

- **Principle**
  
  Moves from start point $P_s(X_s, Y_s, Z_s)$ to reach the end point $P_e(X_e, Y_e, Z_e)$ at time $t = T_i$. $T$ is the sampling time.
  
  The grid density (number of subintervals $N$): $N$ is rounded to the nearest integer, equal to or greater than $T_i/T$.
  
- **Velocity components of $V$**

$$
V_x = \frac{X_e - X_s}{\sqrt{(X_e - X_s)^2 + (Y_e - Y_s)^2 + (Z_e - Z_s)^2}} \cdot V
$$

$$
V_y = \frac{Y_e - Y_s}{\sqrt{(X_e - X_s)^2 + (Y_e - Y_s)^2 + (Z_e - Z_s)^2}} \cdot V
$$

$$
V_z = \frac{Z_e - Z_s}{\sqrt{(X_e - X_s)^2 + (Y_e - Y_s)^2 + (Z_e - Z_s)^2}} \cdot V
$$

- **Incremental coordinates required to move**

$$
\Delta X = V_x \cdot T = \frac{X_e - X_s}{\sqrt{(X_e - X_s)^2 + (Y_e - Y_s)^2 + (Z_e - Z_s)^2}} \cdot V \cdot T = \lambda_t FRN \cdot (X_e - X_s)
$$

$$
\Delta Y = V_y \cdot T = \frac{Y_e - Y_s}{\sqrt{(X_e - X_s)^2 + (Y_e - Y_s)^2 + (Z_e - Z_s)^2}} \cdot V \cdot T = \lambda_t FRN \cdot (Y_e - Y_s)
$$

$$
\Delta Z = V_z \cdot T = \frac{Z_e - Z_s}{\sqrt{(X_e - X_s)^2 + (Y_e - Y_s)^2 + (Z_e - Z_s)^2}} \cdot V \cdot T = \lambda_t FRN \cdot (Z_e - Z_s)
$$

$V$—Programmed feedrate (mm/min)

$T$—Interpolation period (ms)

$\lambda_t$—time constant after interpolation, $\lambda_t = T \times 10^{-3}/60$. 

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Extended DDA Interpolation

- **Principle**
  - **Number of feedrate**
    - \[ \text{step coefficient } \lambda_d = \text{FRN} \times \lambda_t \]
    - \[ \text{FRN} = \frac{V}{\sqrt{(X_e - X_s)^2 + (Y_e - Y_s)^2 + (Z_e - Z_s)^2}} \]
  - **Coordinate values for moving point**
    - \[ \begin{cases} 
      X_{i+1} = X_i + \Delta X \\
      Y_{i+1} = Y_i + \Delta Y \\
      Z_{i+1} = Z_i + \Delta Z 
    \end{cases} \quad (i = 1, 2, \ldots, n) \]
    - \[ \begin{cases} 
      \Delta X = \lambda_d (X_e - X_s) \\
      \Delta Y = \lambda_d (Y_e - Y_s) \\
      \Delta Z = \lambda_d (Z_e - Z_s) 
    \end{cases} \]
Feedrate Design for Feedrate Difference

Feedrate difference for X axis is large, feedrate for X axis is discontinuous.

Feedrate difference for Y axis is large, feedrate for Y axis is discontinuous.

Feedrate difference for X axis is small, feedrate for X axis is more continuous.

Feedrate difference for Y axis is small, feedrate for Y axis is more continuous.

Photo Taken From: FANUC
### Acceleration/Deceleration Design

#### O0001

- N10 G0 X0 Y0
- N20 G01 X20 Y20 F1000
- N30 X40 Y0
- ...
- M30

---

**Diagram:**

- **Tangent feedrate**
  - N20
  - Machine vibrates
  - Time

- **Tangent acceleration**
  - Machine vibrates
  - Time

- **Tangent feedrate**
  - N20
  - Machine vibration reduces
  - Time

- **Tangent acceleration**
  - Machine vibration reduces
  - Time
Types of ACC/DEC

Three common types of ACC/DEC for commercial controllers

- Linear Acceleration/Deceleration
- Exponential Acceleration/Deceleration
- Bell-shaped Acceleration/Deceleration
Path Error Reduction with G-Code

- Desired machining trajectory
- Actual machining trajectory with using after federate interpolation

- Path error due to using after interpolation feedrate controlling could be eliminated by adding G04 or G09 between two blocks.

- G04: Dwell For Precise Timing
  - It keeps the axes unmoving for the period of time in seconds specified by the P number.

- G09: Exact Stop Check
  - It causes the machine to wait until the cutter is finished and exactly on position before continuing.

Photo Taken From: Internet
SIEMENS Exact Stop Function

- **Exact Stop Coarse and Fine**

<table>
<thead>
<tr>
<th>G function</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>G601</td>
<td>Exact stop fine</td>
</tr>
<tr>
<td>G602</td>
<td>Exact stop coarse</td>
</tr>
<tr>
<td>G603</td>
<td>Interpolation end</td>
</tr>
</tbody>
</table>

Exact stop coarse  
(MD36010)  >  
Exact stop fine  
(MD36000)
Look-ahead Function

- Increasing feedrate to shorten machining time
- Reducing a machine vibration caused by acc/dec control of piecewise line segments
Look-ahead Bell-shaped Acc./Dec.

- Look-ahead Linear Acc./Dec. Before Interpolation
- Look-ahead Bell-Shaped Acc./Dec. Before Interpolation

Substitutes bell-shaped with linear acc./dec.

Smoother Acc./Dec.

Reduce machine vibration an shock

Photo Taken From: FANUC
Deceleration by Acceleration

- Limit for each axis’s max acceleration to reduce a machine vibration caused by large acc/dec.
Jerk is the derivative of acceleration with respect to time.
Jerk Control

Line block (N1) connects circular block (N2)

Vibration due to acceleration change

Limit axial max. acc. variation (Jerk)
Jerk Control

Max. acc. variation

From straight line to arc
Specified feedrate: 6000 mm/min
Arc radius: 10 mm

Acceleration change amount:

\[ A_y = \frac{F^2}{r} = \frac{(6000 \text{ mm/min})^2}{10 \text{ mm}} = 1000 \text{ mm/sec}^2 \]

Jerk Limitation

Photo Taken From: FANUC & SIEMENS
Linear vs. Parametric Interpolation

- High-end CNC
  - FANUC: Nano Smoothing I & II
  - MITSUBISHI: SSS4(Super Smooth Surface4)
  - SIEMENS: Compressor
  - HEIDENHAIN: Contour Filter (M124)

1. No errors for using small line segments to approximate curves
2. Compression for part programming file’s size
3. Increasing machining feedrate
4. Do need to transfer files through DNC
Smoothing Control

- **FANUC Nano Smoothing I/II**
  - Related G-code
    - G5.1 Q3(Enable)
    - G5.1 Q0(Disable)
Smoothing Control

- **MITSUBISHI SSS (Super Smooth Surface)**
  - With look-ahead blocks by judging part program paths, unnecessary deceleration is reduced, even when fine steps in the program exist. This provides a smooth finish without deviation for die-mold machining.

- It compensates uneven paths output from CAM to smoothly joint the tool center points' path.

- This function suppresses the vibrations of the tool by moving the rotary axis smoothly.
Smoothing Control

- **MITSUBISHI SSS4(Super Smooth Surface 4)**

  - Optimum speed control is always performed even with a program with an error, resulting smooth surface in short time.
  - Machining time can be shorter by 5 to 30% relative to a conventional system, especially more effective at a higher feed rate.
Smoothing Control

- **SIEMENS Compressor**
  - In accordance with the specified tolerance band, the compressor takes a sequence of G1 commands, combines them and compresses them into a spline
    - **COMPON/COMPCURV**
      - 10 blocks as a set for curve fitting with three or fifth order polynomial equations
    - **COMPCAD**
      - All blocks combined and compressed into a B-Spline
Smoothing Control

- **HEIDENHAIN Contour Filter (M124)**
  - **Shape of Contour Transitions**
    - Tangential circle \([M\text{P}7415.0 = 0]\)
    - Third-degree polynomial (cubic spline) \([M\text{P}7415.0 = 1]\)
    - Fifth-degree polynomial \([M\text{P}7415.0 = 2]\)
    - Seventh-degree polynomial (standard setting) \([M\text{P}7415.0 = 3]\)
  - **Rounding of Contour Transitions**
    - Do not round the contour transition \([M\text{P}7415.1 = 0]\)
    - Round the contour transition \([M\text{P}7415 = 1]\)

**Constraints:**
- Permissible contour deviation \(T\)
- Minimum length \(E\) of a contour element


<table>
<thead>
<tr>
<th>Order</th>
<th>Position</th>
<th>Velocity</th>
<th>Acc.</th>
<th>Jerk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Second</td>
<td><img src="#" alt="Graph" /></td>
<td><img src="#" alt="Graph" /></td>
<td><img src="#" alt="Graph" /></td>
<td>Acceleration can not be differentiated</td>
</tr>
<tr>
<td>Third</td>
<td><img src="#" alt="Graph" /></td>
<td><img src="#" alt="Graph" /></td>
<td><img src="#" alt="Graph" /></td>
<td>加速度不可微分</td>
</tr>
<tr>
<td>Fourth</td>
<td><img src="#" alt="Graph" /></td>
<td><img src="#" alt="Graph" /></td>
<td><img src="#" alt="Graph" /></td>
<td></td>
</tr>
</tbody>
</table>

階數越高，軌跡越平順。
低階控制器：2階，外加jerk濾波。
高階控制器：3階以上，或其他機制，但至少jerk為連續。
Motion Command and Feedforward

Motion Command Generation

◆ How to minimize (position) error?

- Increasing system’s BW
- Advanced motion command and external disturbance cancellation

➢ Force feedforward):

✓ Controller’s output with pre-calculated force is added directly to the controller’s output

✓ \[ F = m \cdot acc + d \cdot vel + \ldots \]
Motion Command w/o Feedforward

- Motion Command Generation
  - How to minimize (position) error?
    - Target: position, velocity, acceleration and jerk

No position error (PE), no control action (force)

MCG: Motion Command Generator
PE: Position Error
Motion Command w/ Feedforward

Motion Command Generation

- How to minimize (position) error?

Target: position, velocity, acceleration and jerk

MCG: Motion Command Generator

PE: Position Error
Motion Command w/ Feedforward

- Motion Command Generation
  - Acceleration feedforward

FF's effect for 2nd order system (PD control)
Motion Command w/ Feedforward

- Motion Command Generation
  - Acceleration feedforward

FF’s effect for 2nd order system (PID control)

- w/o FF
- w acc. FF
Motion Command and Feedforward

Motion Command Generation

- Motion command generation is added to sampling process

Read input(s) → Motion cmd calculation(s) → Control cmd calculation(s) → Write Output(s)

$T_s$ (Sampling time)

Better solution?
General Motion Control Platform

Before

<table>
<thead>
<tr>
<th>CPU Card</th>
<th>HMI Module</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motion Module</td>
<td></td>
</tr>
</tbody>
</table>

Motion Control Chip

Now

<table>
<thead>
<tr>
<th>CPU Card</th>
<th>HMI Module</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motion Module</td>
<td></td>
</tr>
<tr>
<td>Digital Motion Control Chip</td>
<td></td>
</tr>
</tbody>
</table>

Dedicated CPU for Motion Module
Hardware Design

- ITRI CNC Controller
  - Before: IPC card + Motion control card
    - high cost, bulky, poor stability
  - Now: IPC Card + Motion Control Card
    - low cost, small size, good stability

- SOC-based Precision Motion Control Card
- Dual-CPU Dual-OS CNC Controller
Software Design

- IPC’s CPU for HMI
- Motion control card’s CPU for motion control kernel

Feature:
1. Integration of motion control chip, SOC and IPC card in a SOC-based CNC control device

Feature:
2. Integration of motion control kernel, axes control with FIFO, PLC and HMI communication interface
Dual-CPU Dual-OS CNC Controller

- GMC Controller (Half-Size Rack)

- GMC Motion Control Card
- IPC Card
- 3D Accelerated Graphics Card

Option: 3D simulation with 3D acceleration graphics card
Controller Hardware Architecture

- Compact Package

- 15” Industrial touchscreen
- M100Touch controller
- Operation panel and full-key keyboard
- GMC motion control card
- Handwheel control
- Adapter plate
- Universal/Serial servo system
Controller Hardware Architecture

- ITRI M100Touch-5A
  - 座標顯示
  - PLC 階梯圖及IO狀態顯示
  - 2鍵式直覺觸控操作
  - 3D切削模擬
  - 儀製化軟體面板
  - 雷射量測
  - 常用系統資訊列及工具列
  - 參數說明及搜尋
Controller Hardware Architecture

ITRI M5A(GMC/RTX)

人機介面裝置 | 控制器主機

週邊轉接板

五軸伺服

運動控制軸卡

SLAVE I/O -1

SLAVE I/O -2

週邊轉接板

人機介面装置 控制器主機

Demo Kit

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ITRI M5A(GMC/RTX)

Controller Hardware Architecture
Controller Hardware Architecture

- ITRI M5A (EtherCAT)
- HMI (Human Machine Interface) Device, Controller

- Touch Screen
- Keyboard
- Mouse
- IPC (Industrial Personal Computer)
- IO Card
- Peripheral Equipment

Real-time for Windows

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Machine Center Controller

1. Spindle System
2. Feed System
3. Controller Rack
4. Controller Hardware
5. Controller Software
6. Electronic Control Applications
High-speed High-precision Control

- **Milling for Die and Mold**
  - High-speed high-precision contouring control
  - Look-ahead 1000 Blocks
  - S-curve ACC/DEC
  - IPO time 1.0ms
  - Automatic Feedrate Control (Deceleration based on the feedrate difference at a corner)
  - B-spline and nano interpolation

- **Tapping**
  - Rigid tapping
  - Zero phase error tracking control

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Five-axis Precision Interpolation Control

Five-axis Machining
- Supported three types (TTTRR, RTTTR, RRTTT)
- Tool center point control
- Virtual tool axis retract
- Tool posture control
- Tilted working plane machining
- Rotary axes error compensation
- Workpiece setting error compensation
- 3D online anti-collision
- 3D machining simulation
Turn-mill Multi-tasking Control

- Turn-mill Machining
  - Dual-spindle simultaneous control
  - Dual system of turn-mill
  - X and C axes milling synchronously
  - Inside/outside diameter turning
  - Indexing control of the B-axis
  - Virtual Y-axis function

Virtual Y-axis

3D anti-collision

Rigid tapping

X and C axes synchronously
## Robot Arm Controller

<table>
<thead>
<tr>
<th>Item</th>
<th>Spec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monitor</td>
<td>8.4” TFT LCD (with Touch screen)</td>
</tr>
<tr>
<td>CPU</td>
<td>1.66GHz(HMI), 800MHz(Motion)</td>
</tr>
<tr>
<td>RAM</td>
<td>512MB(HMI)</td>
</tr>
<tr>
<td>Graphic</td>
<td>GMA3150 (Opt.GeForce 8400)</td>
</tr>
<tr>
<td>Controlled Axes</td>
<td>32</td>
</tr>
<tr>
<td>I/O Port</td>
<td>64 / 64 (Opt.512 / 512)</td>
</tr>
<tr>
<td>Storage</td>
<td>4G CF Card / USB</td>
</tr>
</tbody>
</table>

### Diagram

- 8.4” Touch Screen
- Controller
- Wireless keyboard
- Teach In Device
- Safety Devices
- Terminal Board
- Motor and Driver

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Industrial ROBOT Control

四軸水平關節工業機器人
EtherCAT控制

具備點對點、直線、圓弧運動控制指令/命令解析度1μm(0.001°)

座標維護與指令模式包含[卡式座標]、[關節座標]與[Tool座標]

全數位控制系統：配線維護簡單、抗雜訊干擾能力高及安全可靠性高

友善操作機能:直覺式功能切換選單、程式編輯、手動教導輸入模式、手臂參數設定、MLC程式編輯、伺服參數設定、模擬手臂運作、料盤設定、輸送帶取料(4+2軸應用)

EtherCAT
EtherCAT
EtherCAT
Ethernet

MLC程式編輯介面
(可客製化手臂&加值軟體&四合一驅動器)
Industrial ROBOT Control

- Six-axis Architecture Robot
  - Kinematics and singular points estimation
  - Point to point, line/circular interpolation
  - Coordinate maintenance for Cartesian, Joint and Tool
  - All-digital series servo system and absolute coordinate
  - Position error compensation calibration function
  - Modes for teach-in, programming, guidance
  - PLC embedded
  - Virtual robot-machine simulation
    - Collision warning module
    - Part set ready module
    - Fixture set ready module
    - 3D motion simulation module
Industrial ROBOT Control

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Intelligent Robotization Control

- Robot Inside CNC
  - Kinematics and singular points estimation
  - Coordinate maintenance for Cartesian, Joint and Tool
  - All-digital series servo system and absolute coordinate
  - Virtual robot-machine simulation
    - Collision warning module
    - Part set ready module
    - Fixture set ready module
    - 3D motion simulation module
Integration of Robots

- HMI design
  - CNC with built-in ROBOT
Friendly, Open Man-machine Interface

- Coordinate display
- PLC ladder and IO status
- Intuitive touchscreen
- 3D machining
- Customized software
- Common Info and toolbar
- Laser measurement
- Parameter and search
Servo Drive

Servo Motors in CNC Machine

- Spindle motor
- Feed braking motor
- Feed servo motors
- Tool magazine positioning motor
- Auto tools change rotary positioning motor
Servo Drive

- Feed axes controlled in CNC machine

Vertical three-axis machine center

Horizontal (vertical) five-axis machine center
CNC Machine Driving System

- Classified

1. Spindle Drive
   - It is used to provide angular motion to the workpiece or a cutting tool.

2. Feed Drive
   - It is used to drive the slide or a table.
   - It consists of an electromotor and mechanical transmission elements.
Feed Closed Loop Control

- **Semi-closed Loop Control**
  - Xnormal
  - Position control
  - Speed control
  - Rotary encoder

- **Full-closed Loop Control**
  - Xnormal
  - Position control
  - Speed control
  - Rotary encoder
  - Xactual
  - Linear scale
Feed Drive Servo System

- Capable of handling low-frequency vibration to high-frequency vibration
- Exercise current control at high speed
- Detect current with high precision

High-response, high-precision detector
Servo Positioning

- Open-loop
- Closed-loop

Diagram:

- Motor
- Ballscrew
- Load
- Controller
- Photoelectric encoder
- Position feedback signal
- Control command
Servo System

Component:
- Converter circuit of driven control signal
- Power amplifier module
- Position regulation unit (position loop)
- Velocity regulation unit (velocity loop)
- Current regulation unit (current loop)
- Detect measurement

Controller, PLC...

Servo drive system (servo motor)

Detection (Sensor)

Load (Ballscrew...)

Servo drive system (servo amplifier)

Photo Taken From: Internet
Servo Characteristic Data

- Torque-Speed Curve of a DC Servomotor and Load Torque Plot

Torque, $T$ vs. Speed, $\omega$ for different types of servos:
- Stepper
- AC Servo
- DC Servo

Operating Points and Load
Servo Characteristic Diagram

DC Brushless motors

- Starting torque: 0.238 [N.m]
- Short-term: 0.159 [N.m]
- Rated point
- Continuous operation

- Torque vs Speed [r/min]
- Power vs Speed [kRPM]
- Vehicle Max. climb Capability

- 功率特性曲線
- 轉矩特性曲線
Open and Closed Loop Servo System

(1) Open loop
• No measured device

(2) Semi closed loop
• Sampled rotation angle detected by encoder

(3) Fully closed loop
• Position directly detected from mover by scale
Three Common Servo Control Modes

- **Pulse Command**
  - Pulse command for driving step motor

- **Position Command (Pulse Format)**
  - Position command (pulse format) for driving servo motor and feedback via encoder

- **Velocity Command (Voltage Format)**
  - Velocity command for driving servo motor and feedback via tachometer.
Position Servo Control

Position control ⇒ control the amount of movement (motor’s rotation angles)

➢ Two situations:

(1) Point to point control
(2) Trajectory control
Velocity Servo Control

- Velocity control $\Rightarrow$ control the rotational speed

![Diagram of Velocity Servo Control System]

- Velocity cmd (Analog) -> Amplifier
  - I loop
  - Torque cmd
  - Torque generation
  - Velocity sensor

- $V_{cmd}$
  - speedmi
  - $n-1$
  - 1000
  - 0
  - 2 V
**Torque Servo Control**

- **Input:** desire torque command (analog)

![Torque Servo Control Diagram](image)

- **Torque cmd** (velocity cannot be controlled)
- **Amplifier**
- **Load torque**

**Diagram Details:**
- **Tcmd**
- **Tl**
- **Vα**
- **Tps**
- **Torque**

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Joe Lee 89
Servo System Control Architecture

- **System Layers**
  1. **Upper Control — Motion control card**
     - Motion control: *interpreter, trajectory plan, acc/dec…*
  2. **Lower Control — Servo Drive**
     - Internal control loop of servo drive

- **Three control loop**
  1. **Current loop**
     - Enhance system response, suppress internal disturbance of current loop
  2. **Velocity loop**
     - Strengthen anti-disturbance load ability and speed fluctuation supression
  3. **Position loop**
     - Ensure static accuracy and dynamic tracking

---

[Diagram of Servo System Control Architecture]

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Servo System Feedback Control
CNC Feed Drive Servo System

- SIMODRIVE 611D servo drive system

**Diagram:****

- Position controller
- Velocity controller
- Setpoint filter
- Position gain ($K_v$)
- Velocity gain ($K_p$)
- Velocity integral time ($T_n$)
- Feedforward compensation

**Components:**

- Rotary encoder
- Linear encoder
- Bearing
- Screw
- Nut
- Base structure

**Photo Taken From:** SIEMENS
CNC Servo Control Architecture

- SMODRIVE 611D Servo Loop System Variables
  - Rough IPO
  - Fine FIPO

Photo Taken From: SIEMENS
Servo Motor Modeling

- Circuit
- Rigid body motion
- Back emf eq.
- Motor torque

La : Armature inductance ($H$)
Ra : Armature resistance ($Ω$)
Kb : Back electro-motive force ($V/\text{rad/sec}$)
Kt : Torque constant ($Nm/A$)
Jm : Moment inertial of motor ($Kgm^2$)
Bm : Viscous damper ($Nm/(\text{rad/sec})$)

\[ \frac{di_a}{dt} + Ri_a + E_a = V \]
\[ J \frac{d^2\theta}{dt^2} + B_m \frac{d\theta}{dt} = T_m \]
\[ E_a = K_E \omega_m (\text{back emf}) \]
\[ T_m = K_T i_a \]
\[ K_T = K_E = \left( \frac{n_a lr}{2} \right) B_f \]
Servo Motor Modeling

- **Transfer Function**
  
  1. **Circuit**
     
     \[ L_a \frac{di_a}{dt} + R_a i_a + E_b = E_a \Rightarrow (L_a s + R_a)I_a(s) = E_a(s) - E_b(s) \]
     
     \[ \Rightarrow I_a(s) = \frac{1}{L_a s + R_a} (E_a(s) - E_b(s)) \]  
     
  2. **Back emf**
     
     \[ E_b = k_b \dot{\theta} = k_b \omega \Rightarrow E_b(s) = k_b \omega(s) \]  

  3. **Rigid body motion**
     
     \[ J_m \frac{d\omega}{dt} + B_m \omega = T_m \Rightarrow (J_m s + B_m)\omega(s) = T_m(s) \]
     
     \[ \Rightarrow \omega(s) = \frac{1}{(J_m s + B_m)} T_m(s) \]  

  4. **Motor torque**
     
     \[ T_m = K_i i_a \Rightarrow K_i i_a(s) = T_m(s) \]
Servo Motor Modeling

- Servo Motor Modeling
- Open Loop System Block Diagram

\[
\begin{align*}
E_a(s) & \xrightarrow{+} \frac{1}{L_a s + R_a} I_a(s) \xrightarrow{-} T_m(s) \xrightarrow{+} \frac{1}{J_m s + B_m} \omega \xrightarrow{-} \frac{1}{s} \theta \\
E_b(s) & \xrightarrow{-} K_b \xrightarrow{+} E_a(s) \xrightarrow{-} \frac{K_t}{L_a s + R_a} \frac{1}{J_m s + B_m} \omega \xrightarrow{-} \frac{1}{s} \theta \\
E_b(s) & \xrightarrow{-} K_b \xrightarrow{+} E_a(s) \xrightarrow{-} \frac{1}{s} \theta
\end{align*}
\]
Servo Motor Modeling

- Servo Motor Modeling
- Closed Loop System Block Diagram

\[
G(s) = \frac{\frac{K_T}{L_a} J_m s^2 + \frac{R_a J_m + L_a J_m}{s} + \left(B_m R_a + K_T K_b\right)}{L_a J_m s^2 + \left(R_a J_m + L_a J_m\right) s + \left(B_m R_a + K_T K_b\right)}, \text{Assume } B_m = 0
\]

\[
G(s) = \frac{\frac{K_T}{K_T K_b}}{\frac{L_a J_m}{K_T K_b} s^2 + \frac{R_a J_m + L_a J_m}{s} + \frac{1}{s+1}} = \frac{1/K_b}{(1+\tau_e s)(1+\tau_m s)}
\]

Note: \( L_a i_a + R_a i = V \) \( \Rightarrow \) \( I(s) = \frac{1}{V(s)} = \frac{1}{L_a s + R_a} \)

\( \tau_m = \frac{R_a}{K_T K_b} \)

\( \tau_e = \frac{L_a}{R_a} \)
Servo Motor Block Diagram

Servo Motor Modeling

\[ P_{in}(s) \]
\[ V_{in}(s) \]
\[ K_{pp} \]
\[ K_{p} + \frac{K_{t}}{s} \]
\[ K_{p} + \frac{K_{t}}{s} \]
\[ 1 \]
\[ L_{a}S + R_{a} \]
\[ \frac{1}{s} \]
\[ K_{b} \]
\[ K_{s} \]
\[ P_{out}(s) \]

\[ K_{2} \] : Current feedback constant (V/A)
\[ K \] : P gain of velocity controller (1/sec)
\[ K_{p} \] : P gain of velocity controller
\[ K_{i} \] : I gain of velocity controller
\[ K_{d} \] : D gain of velocity controller

- \( L_{a} \) : Armature inductance (H)
- \( R_{a} \) : Armature resistance (Ω)
- \( K_{t} \) : Torque constant (Nm/A)
- \( J_{m} \) : Moment of inertia of motor (Kgm²)
- \( B_{m} \) : Viscous damper (Nm/(rad/sec))
- \( K_{v} \) : Velocity feedback constant (m/rad)
- \( T_{m} \) : Torque of motor (Nm)
- \( T_{l} \) : Torque of load (Nm)
The bandwidth of electric circuit is faster than rigid body system, it is regarded as **first order model** form current input to angular speed output.

\[
\frac{\omega(s)}{I_{\text{cmd}}(s)} = \frac{K_t}{(J_m s + B_m)} = \frac{b}{s + a}
\]
Servo Motor Modeling

Open Current Loop System Block Diagram

Design position velocity and velocity feedforward controller according to user’s specifications.
Servo Motor Modeling

Open Current Loop System Block Diagram

Design the P-I controller:

Choose the damping and bandwidth:

\[ G_v(s) = \frac{K_v s + K_w b}{s^2 + (a + K_v b)s + K_w b} \]

\[ K_v = \frac{\omega_n^2}{b} \]

\[ \omega_n = \sqrt{a + K_v b} \]

\[ \omega_n = \frac{25\omega_n^2 - a}{b} \]
Inverse Laplace

Servo Motor Modeling

Open Position Loop Block Diagram

\[ Y(s) = \frac{R(s)}{R(s) + K_{pp} + \frac{K_{pp}}{s} + \frac{K_{pp}}{s+a}} \]

\[ y(t) = K_{pp} r(t) \]
FANUC Controller Architecture

- **FANUC 30i**

  State-of-the-Art High-Speed, High Reliability Hardware
FANUC Controller Architecture

- FANUC 30i
  - FSSB link servo and spindle
  - Synchronous error reduction between rigid tapping servo and spindle
  - FSSB: Fiber+ECC (Error Correction Code)
FANUC 30i Series

Feature

- 64-bit RISC micro processor chip
- AI nano contouring control
- AI high precision control
- HRV4 (High Response Vector 4) control
- CNC: 96 axes (72 feed axes, 24 spindles) / 10 pathes, 72 axes (56 feed axes, 16 spindles) / 15 pathes; Max. number of simultaneous controlled axes: 24 axes.
- PMC: dedicated processor and dedicated LSI, max. supported for five paths
- Servo: DSP-base servo processor and high-speed FSSB protocol
- Lookahead: 1000 blocks
- PC function with Windows OS: FANUC PANEL I is an enhanced commination of a CNC and PC with a original high-speed interface.

FANUC AI nano control system

Photo Taken From: FANUC
FANUC 30i Series

- **Feature**
  - AI nano contouring control
    - reduction position lag due to acc/dec and servo lag
  - Smooth TCP
    - stable/high precision machining process
  - Five-axis machining function
    - TCP/tilted work plane/TPC
  - Adaptive predictive control (APC)
  - SERVO GUIDE tuning software
  - 3D interference check
  - CIMPLICITY i CELL
    - multiple CNC network management
FANUC 30i Series

- High-Speed, High-Quality Machining
  - Nano CNC System
  - Nano Interpolation
  - AI Contour Control I/ AI Contour Control II
    - Advanced lookahead algorithms evaluate the programmed path to determine the optimal federate and acceleration resulting in reduced cycle times and improved accuracy.

- Smooth Tolerance+ Control
  - Automatically generates a smooth curve for a machining specified with continuous small blocks and also within the specified tolerance to reduce mechanical shock and improves the quality of the machined surface.
FANUC 30i Series

- Advanced Digital Servo Technology
  - Smart Machine Control
  - SERVO HRV (High Response Vector) Control
  - SPINDLE HRV (High Response Vector) Control
  - Smooth Tolerance+ Control

Photo Taken From: FANUC
FANUC 30i Series

- 5-axis machining functions achieves a smooth, high-speed and high-precision machining
  - Tilted working plane indexing
  - FANUC SERVO GUIDE 3-D View Function
  - High-speed Smooth TCP
  - High-precision simultaneous 5-axis machining using Smooth tolerance+ control
FANUC 30i Series

- Flexible Support of Various Mechanical Configurations
  - Expanded multi-axis and multi-path functions
  - Multi-path program management function (max 3 programs)
  - Peripheral axis control

- Consistent support at shop floor
  - FANUC iHMI
  - Expanded multi-axis and multi-path functions
**Easy Incorporation into Machine**

- **High-Speed and Large-Capacity**
  - Program capacity: max. 300,000 steps
  - Internal relay(R): max. 60,000 bytes
  - Data table(D): max. 60,000 bytes
  - PMC paths: max. 5 paths (max. 40 ladder programs)
  - Advanced lookahead algorithms evaluate the programmed path to determine the optimal federate and acceleration resulting in reduced cycle times and improved accuracy.

- **Multi-path PMC**
  - One PMC can execute up to 5 independent ladder programs.

- **Function Block function**
  - This function is used to call up repeatedly used ladder circuit patterns in blocks.
  - PMC axis control and peripheral equipment control, are provided by customizable function blocks as PMC Function Library in FANUC LADDER-III’s CD.

**Dual Check Safety + Servo STO**

- It conforms to the ISO 13849-1 Pl d.
- Two PMC functions provide duplicate paths of breaking power for the servo/spindle amplifier.
- STO (Safe Torque Off function) is equipped in the servo amplifier. Power lines for the motor can be shut off without using the electro-magnetic conductor.
FANUC 30i Series

- **PC function with Windows OS**
  - PC functions bring a lot of enhancement through up-to-date computer and information technology for intelligent machine tools.

- **Network Support Functions**
  - **Ethernet/Industrial Ethernet/Field network**
  - **FANUC MT-Link i (Operation Management software)/FANUC OPC Server**
SIEMENS TIA

- Totally Integrated Automation

- SIMOTION
  - Motion Control System

- SINUMERIK
  - Computer Numerical Control

- SIMATIC Controllers
  - Modular/Embedded/PC-based
SIEMENS Sinumerik System

- SINUMERIK CNC
  1. CNC HMI
  2. CNC controls
  3. CNC Operate
     - ShopMill
     - ShopTurn
  4. SINUMERIK Safety Integrated
SIEMENS CNC Controls Architecture

1. HMI (MMC)
2. NCU
3. PLC

Numerical control unit
Drive unit

Photo Taken From: SIEMENS
SIEMENS 840D Architecture

Three CPUs:
1. MMC-CPU
2. NC-CPU
3. PLC-CPU

Four software:
1. MMC
2. NC
3. PLC
4. communication/drive interface
SIEMENS NC Control and Servo

- 840D + 611D

System control and display module

Power module I/R

Control module

Servo drive module 611D

PCU50

Windows

Operator panel/keyboard /handwheel

NC+PLC

Drives

Spindle motor

Feed motors

Photo Taken From: SIEMENS
SIEMENS Controller Structure

840D + 611D
 Specifications:

- **32-bit micro processor** (828D:80bits nano precision floating operation)
- High-speed and high-precision
- NC file compressor
- Acc/dec feedforward control for contouring error suppression
- Jerk limit control for surface quality
- Active vibration control
- CNC: Up to 30 machining channels. Up to 93 axes/spindles
- Lookahead: 1,000 blocks

**SIEMENS SINUMERIK control system**
SIEMENS 840D sl Series

Feature

- Advanced surface control
  - high order surface + Look-ahead

- ShopMill/ShopTurn sequence programming editor
  - Flexible readability editor language

- Five-axis machining function
  - TRAORI/ CYCLE996/CYCLE800

- High-speed machining function (CYCLE832)
  - Speed/accuracy/surface auto adjustment

- Dynamic Stiffness Control (DSC)
SIEMENS Simulation and Validation

- Virtual NC Kernel (VNCK)
  - Machining process graphic simulation/verification

- Mechatronic Support
  - Mechatronics design and development
  - Dynamic response analysis
  - Optimal control parameters
  - Shorten process development
HEIDENHAIN Controls Architecture

- iTNC 530
HEIDENHAIN iTNC530 HSCI Series

- Specification
  - 32-bit micro processor
  - MC 6341 main CPU - Pentium Dual Core with 2.2GHz processor
    - Machine Controlled: HEIDENHAIN dedicated real-time OS (HeROS 5)
    - Man-machine interface: Windows 7 OS
  - CC 6110 control unit - DSP
  - CNC: 1 path, 20 controlled axes (3 rotary axes, 2 spindles)
  - Lookahead: 1024 blocks

HEIDENHAIN contouring control system

Photo Taken From: HEIDENHAIN
HEIDENHAIN iTNC530 Series

Feature

- SmarT.NC programming editor
  - dialogue without remembering G-code
- DXF converter
  - DXF files imported to directly generate NC file
- Five-axis machining function
  - tool center point management/tilted plane/five-axis errors measurement and compensation
- Dynamic collision monitoring technology (DCM)
  - real-time multi-axis machining interference collision inspection
- Adaptive feedrate control (AFC)
  - machining time reduction
  - tool monitoring
  - machine failure rate reduction
FIDIA Controller Architecture

- C20/C40
FIDIA C40 Vision Series

- Specification
  - 32-bit micro processor
  - Two independent processors
  - 400 MHz RISC Power CPU
  - Real-time motion control
  - 3.4GHz Intel Core i7 四核心CPU，Window 7 Ultimate 64bit
  - Man-machine interface management
    - CNC: 1 path, 32 controlled axes
    - Lookahead: 1000 blocks

FIDIA new age control system
FIDIA C40 Vision Series

Feature

- LookAhead(L.A. FIVE) auto tuning function
  - machine types, workpiece types, machining demand (rough, semi-finishing, finishing)
- Five-axis machining function
  - RTCP/tilted plane/virtual tool axis
- Look Ahead Virtual Milling Simulation
- HI-MILL - 3D CAM
- PLP – copying function
- HMS rotary axes measurement system
Intelligent Manufacturing System

- **Smart Machining System**
  - **US Automotive Industry**
    - **Conservative Machining**
      - Lacking reliable online monitoring technique
      - 58% allowed cutting speed and 38% allowed tool life
      - Loss of about $10 billion per year
  - **US Aircraft Industry**
    - **Conservative Maintenance**
      - Lacking intelligent monitoring technique
      - One thousand consumable spindles in a large manufacturer, one spindle’s operation life is about 40~400 hours
      - Equipment maintenance fee is about $500 billion per year
      - Saving $100 billion per year with intelligent monitoring technique
Trend 1: High Speed High Precision

1. High-speed Spindle
   ◆ 20,000-200,000rpm

2. High-speed Feed
   ◆ Rapid moving (G00)
     ○ 60m/mim-240m/mim
   ◆ Cutting moving (G01/G02)
     ○ 60m/mim
   ◆ Acceleration
     ○ 2-3G

3. Resolution
   ◆ 1um-1nm

4. ATC Speed
   ◆ Less than 1sec
1. Nano Control

- **FANUC 30i**
- **AI Contour Control II**
  - encoder resolution is 16million pulses/rotation
  - Interpolation is at the nano-unit level even when program commands are in micrometer units.

- **MITSUBISHI M800V**
  - **Complete Nano Control**
    - All operations from program values to servo commands are done in nanometer units.

- **SIEMENS 840D**
  - **828D : 80-bit Nano FP Resolution**
    - Less than nano-unit level
Trend 1: High Speed High Precision

2. Smooth Control
   - FANUC 30i
     - Nano smoothing
     - High response vector (HRV) control
   - MITSUBISHI M800V
     - Super Smooth Surface-4G (SSS-4G)
       - Tiny difference in level or discontinuous corner caused by CAM internal calculation
       - Errors between control path and machining free surface caused by fixed ISR
       - Trajectory errors caused by servo system’s delay
   - SIEMENS 840D
     - SINUMERIK MDynamics
     - Advanced Surface
     - Compressor
Trend 2: Five-axis Machining

- Utilization rate: 135 hour/week
- Customization: CAM software

- A line for 10 five-axis machines monitored and operated by only 2 operators
- Key factor: Reliability, short processing cycle, thermal protection control

300,000 piece/year

Photo Taken From: INTERNET
Trend 2: Turn-mill Multi-tasking Machining

- Intelligent functions such as active workpiece/spindle balancing control, vibration suppression and anti-collision due to multi-axis multi-tasking machining
MAZAK Turn-mill Machine

- MAZAK Turn-mill Multi-tasking Machine

- Super Multi-tasking Machine-Future Machine Tool
  - Turning, milling, facing, grinding, drilling, laser, measuring...
  - Dry cutting
  - Spindle speed up to 100,000rpm(AMB)
  - Feedrate up to 500m/min & 8G
Trend3: Integration of Robots

- **FANUC - ROBOGUIDE**
  - Integration ROBODRILL machine center and ROBOT M-20iA Robot
  - Automatic loading and unloading, ATC, machining, measuring and assembly....

- **SIEMENS - MyRobot Package**
  - Combination of SINUMERIK CNC controller and industrial robot
  - Automated integration for clamping and transporting

Robot and Factory Automation
CNC-Robot-CMM

Machining Automation

1. Job ID assigned for sorting and processing of program
2. Loading/unloading robot arm
3. Loading and unloading
4. Directly error compensation

Turn-mill Multi-tasking Machine

Coordinate Measuring Machine

Robot Arm

Photo Taken From: INTERNET
Robot integrated CNC Control System

FANUC intelligent Process Automation Solution

Automated Production Unit

Solution 1: one machine and one robot
- 1 FANUC tapping center
- 1 FANCU robot arm

Solution 2: multi machines and one robot
- 1 FANUC vertical mill
- 1 FANUC horizontal lathe
- 1 FANCU robot

Solution 3: multi machines and multi robots with vision integration
- 1 FANUC vertical mill
- 1 FANUC horizontal lathe
- 1 FANCU robot
- 1 CCD inspection system

Photo Taken From: INTERNET
Trend 4: Intelligent Control

- Intelligence for Processing Efficiency and Quality
  - iTNC 530 Adaptive Feed Control
  - 30i Learning Control
  - ITRI Chatter Control

- Intelligence for Driving Performance and Connection
  - 30i Servo Guide for optimal feed/spindle control parameters

- Intelligence for Remote Monitoring and Fault Diagnosis
  - 840D Condition Monitoring for online monitoring and PLC status
OKUMA Intelligent Control

OKUMA THINC-OSP intelligent control

Thermo-Friendly Concept
- Spindle thermal displacement compensation
- Structure thermal displacement compensation

Collision Avoidance System
- 3D virtual machine/tool/workpiece/fixture simulation
- Pre-monitoring for virtual and actual machining

Machining Navi Machining Navigation System
- Machining assistance for operator
- Optimal machining condition and speed for chatter suppression

5-Axis Auto Tuning System
- Automatic measurement of geometric errors with a probe and a standard ball
- Automatic compensation for 13 geometric errors
Intelligent Adaptive Control

- **OMAT** Adaptive Control & Monitoring Technology
  - Spindle current monitoring, adaptive feedrate regulating

- **HEIDENHAIN iTNC 530** Adaptive Feed Control
  - Spindle load monitoring, adaptive feedrate regulating

- **SIEMENS 840D Solution Line** Adaptive Control (ADC)
  - Tool torque monitoring, adaptive spindle speed regulating

- **FANUC 30i** Adaptive Control (i Adapt™)
  - Spindle load monitoring, adaptive cutting feed regulating

Optimizing cutting to achieve maximum metal removal rate
Intelligent Chatter Control

- **Chatter Prediction**
  - Hammer Test
  - TF Measurement
  - Transfer Function (TF)
- **Chatter Control**
  - Modal fitting: natural frequency, damping ratio, modal stiffness
  - Frequency response function (FRF)
  - Chatter stability region of curve: spindle speed, axis cutting depth
  - Stability Lobes

- **Model Analysis**
  - Regenerative chatter theory: simulation for stable chatter area
  - Milling Analysis

Photo Taken From: INTERNET
## OMATIVE ACM and ITRI Controller

### Machining Time Reduction

<table>
<thead>
<tr>
<th>Condition</th>
<th>Machining Time Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>25%</td>
</tr>
<tr>
<td>Optimized</td>
<td>40%</td>
</tr>
</tbody>
</table>

*Photo Taken From: OMAT & ITRI*
Trend 5: Digital Series Servo

- **FANUC 30i**
  - FSSB (FANUC Serial Servo Bus) connected between NC and Servo Amplifiers
  - I/O LINK i connected between NC and I/O device, OP and PMC interface

- **MITSUBISHI M700V**
  - MACH Net (high-speed fiber servo communication network) connected between NCU and Servo
  - MELSECNET (control level network) connected between PLC and PLC or remote I/O
  - CC-LINK (equipment level network) connected to other control equipment

- **SIEMENS 840D**
  - MPI and PROFIBUS connected between NCU and PLC

- **HEIDENHAIN iTNC 530**
  - HSCI (HEIDENHAIN Serial Controller Interface) and EnDat connected between NC and grating scale/encoder

- **FIDIA C40 VISION**
  - FFB (Fast Field Bus) connected between FIDIA Xpower driver and I/O LUX input-output module

All digital CNC control system: digital servo interface, drive unit (position/velocity/current loop), fieldbus and encoder.
MITSUBISHI Intelligent Automated Factory

- Factory Automation Systems
  - MITSUBISHI : e-F@ctory
智能工廠:

透過SMOOTH Technology軟體將資訊技術用於產品設計、製造和管理等全生命週期中，使工藝、程序、計畫等生產準備提前展開。作業者只需讀懂訊息配合機台即可完成任務，實現敏銳響應市場。

5項功能

- SMOOTH CAM RS(編程管理)
- SMOOTH SCHEDULE(日程管理)
- SMOOTH MONITOR(監控管理)
- SMOOTH TOOL MANAGEMENT(刀具管理)
- SMOOTH PMC

Source: MAZAK
OKUMA Dream Factory of the Future

OKUMA - Dream Site 1

『 A Factory of the Future 』

◆ DS1 components:
  1. A Machine Shop
  2. An Assembly Shop

◆ DS1 whole process self-treatment
  - Raw materials input
  - Parts processing
  - Kitting
  - Sub assembly
  - Unit assembly
  - Final assembly
  - Machine runoff
  - Shipment
Trend 6: Green and Safety

- FANUC 30i
  - Energy Monitoring (EM)
  - Energy Saving Level (ESL)
  - Leakage Detection (LDF)
- MITSUBISHI 700V
  - Energy Saving
- SIEMENS 840D Solution Line
  - Ctrl-Energy
  - Integrate
  - Active Line Module (ALM)
- HEIDENHAIN iTNC 530
  - Functional Safety (FS)

Effectively energy consumption of machining process is reduced due to appropriate control strategies, cutting parameters, efficient energy conversion component and drive system energy recovery, etc.
FANUC Energy Saving and Safety

- FANUC 30i
  - Energy Monitoring
  - Energy Saving level

- Safety Detection
Trend 7: Value-added APP

- Friendly Operation and Simply Programming
  - DMG Celos
    - Intuitive touched and holistic user interface
      - Compatible with ERP, PPS, MES, PDM and CAD/CAM
      - 50% faster machine operation and 30% less machine idle time
      - 20% longer machine running time and 30% shorter machine set-up times
  - OKUMA OSP Suite
    - Touched and guided operation interface
      - Intelligent technique
      - Digital factory management
  - MAZATROL SmoothX
    - Touched and interactive interface
      - A single HMI displayed all the important information
      - Plant operation support
  - SIEMENS 840D Operate
    - Graphic user interface
      - Process integration applied to design, programming and operation
  - ITRI
    - Intuitive touched interface
Trend 8: Industry 4.0

Intelligent Manufacturing

DMG MORI ADAMOS

GROB NET4

MAZAK iSMART Factory

MCM In4.0

Source: DMG MORI, Mazak, GROB, MCM Catalogue

Photo Taken From: INTERNET
Trend 8: Industry 4.0

FANUC Intelligent Edge Link and Drive (FIELD) System

- 四社共同開發：Cisco, Rockwell Automation, and Preferred Networks
- FIELD System：提供CNC、機器人和嵌入式感測器來提高整機可靠度、彈性、速度，提升智能工廠整體設備效率和生產利潤。
- ERP（企業資源計畫）
- SCM（供應鏈管理）
- MES（製造執行系統系統）
- ZDT（零停機時間）

- 霧計算(Fog Computing)
- 邊界計算（Edge computing）
  - 網際網路與現實世界的邊界。
Industry 4.0 and Internet of Things (IoT)

- FANUC Intelligent Edge Link and Drive (FIELD) System
The End

Thank You for Your Attention!