課程大綱：
Part I:  Introduction to CNC Machines
Part II:  Interpolator
Part III:  Servo Controller

學業成績：
1st Report:  50% (Interpolator, simulation and evaluation)
2nd Report:  50% (Servo controller, simulation and evaluation)

Part I: Introduction to CNC Machines

[參考資料]
“Control System Engineering”，Norman S. Nise，Benjamin / Cummings Publication Company，滄海書局。
“Introduction to Robotics - Mechanics and Control,” J.J. Crag，Addison-Wesley Publication Company。
“Modern Control Technology - Components and Systems”，Christopher T. Kilian，West Publication Company，高立圖書。
“PCL-833 Encoder卡使用手冊”，研華科技。
“PCL-726 DA卡使用手冊”，研華科技。
“YSDC-1350 直流伺服馬達驅動器使用手冊”，沿興工業。
Chapter 1 Introduction

CNC machines = CNC(Computerized controller) + Machine (machine tool or robotic manipulator)

(1) CNC hardware: computer + interface
(2) CNC software core: logic control + interpolator + servo controller
(3) Mechanisms: ballscrews + guideways + table (for machine tool); gears+joints+links (for robot manipulator)

(A block diagram for 3-axis CNC machines)
1.1 CNC Machine Tools

1.2 Robotic Manipulators
Chapter 2  Positioning Control

2.1 Introduction to Positioning System

(A schematic description for a two-axis positioning system)

一個基本機械定位系統包含: 控制單元(control unit or controller)、驅動元件(drive unit)、位置感測元件(position sensor)。

控制單元：控制電腦及(驅動、感測)界面
驅動元件：馬達、傳動元件
位置感測元件：極限開關、勢能計、編碼器、光學尺
2.2 Controllers

- Microprocessor: Microcontroller, PLC, PC, DSP
- Interface: AD/DA board, Encoder(Counter/Decoder) board
- Language: Assembly, C, MatLab

2.3 Drive Units

2.3.1 Servo Motors

1. Stepper Motors:
   - Permanent Magnet (PM) Stepper Motor
   - Variable Reluctance (VR) Stepper Motor
   - Hybrid Stepper Motor

2. Direct Current Motors:
   - Wound-Filed DC Motor
   - Permanent Magnet DC Motor
   - Brushless DC Motor

3. Alternating Current Motors:
   - Induction Motor
   - Synchronous Motor

2.3.2 Transmission Elements
   - Ball-screw, gear, harmonic gear, belt, bearings

2.3.3 Electronic Drivers (Control Circuits)

2.4 Position Sensors

2.4.1 Proximity sensors
   - Limit Switch
   - Optical Proximity Sensor
   - Hall-Effect Proximity Sensor

2.4.2 Potentiometer

2.4.3 Encoder or linear scales

2.4.4 Decoder and Counter Circuit
   - Potentiometer: (1) Analog feedback or (2) ADC card
   - Encoder and linear scales: Encoder card (decoder and counter circuit)
2.5 Implementation of Driving Axes

(1) Position Feedback

```
Digital Controller -> 驅動器 -> 馬達 -> 傳動元件
```

回授位置(數字)

```
Decoder & Counter <-> pulses
```

Encoder or Linear Scale

機構本體

(2) Position (External) Feedback + Velocity (Internal) Feedback

```
Digital Controller -> 驅動器 -> 馬達 -> 傳動元件
```

回授位置(數字)

```
Tachometer
```

voltage

(3) Position Feedback + (Virtual) Velocity Feedback

```
Digital Controller -> 驅動器 -> 馬達 -> 傳動元件
```

回授位置(數字)

```
DAC
```

虛擬速度

voltage

機構本體
Chapter 3  Controller Design

3.1 Control performance

Control performance: stability, robustness, sensitivity, time response, ...

3.1.1 暫態響應(transient response)

反應速度:
Time Constant: \( \tau \)
Rise Time: \( T_r \)
Peak Time: \( T_p \)

穩定(收斂)速度:
Settling Time: \( T_s \)
Overshoot(超越值): \( OS \)

3.1.2 極點位置(pole location)

(1) First order
\[
G(s) = \frac{K}{\tau s + 1} \\
T_r = 2.2\tau
\]

(2) Second order
\[
G(s) = \frac{K\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \\
\tau = \zeta\omega_n \\
T_p = \frac{\pi}{\omega_n \sqrt{1 - \zeta^2}} \\
T_s = \frac{4}{\zeta\omega_n} \\
P = -1/\tau \\
T_s = \frac{4}{\zeta\omega_n} \\
T_r = 1.1 + 1.4(\zeta - 0.1) \\
OS = e^{-\zeta \pi \sqrt{1 - \zeta^2}}
\]

3.1.3 穩態誤差(steady state error)

(1) System Type：開迴路之積分數

(2) Gain(增益):
\[
G(s) = \frac{K(s + z_1)(s + z_2)\ldots}{s^n(s + p_1)(s + p_2)\ldots} \Rightarrow \begin{cases} 
\text{Type-} n \\
Gain = \frac{Kz_1z_2\ldots}{p_1p_2\ldots}
\end{cases}
\]

(3) 一般伺服馬達定位系統:
Type-1
系統增益=控制器增益×驅動器增益×傳動元件(齒輪、螺桿)增益

3.2 Traditional PID Controller

3.2.1 PID控制：改變極點位置(暫態響應)及增益(穩態誤差)

P控制:
穩態誤差=阻擾(磨擦力、重力)/增益
增益↑ ⇒ 穩態誤差↓
\[T_r\downarrow\]
\[T_p\downarrow\]
\[OS\uparrow\]
\[T_s\]不變

PI控制:
穩態誤差=0
\[OS\uparrow\]
\[T_s\uparrow\]

PD控制:

\[OS\downarrow\]
\[T_s\downarrow\]

PID控制:

\[OS\downarrow\]
\[T_s\downarrow\]

3.2.2 一般PID控制參數設定的經驗法則:
Step-response method
Ultimate-sensitivity method
Lo’s experience:
PD參數：選擇較大之增益。
I參數：適合於磨擦阻力(定位平台)或重力(機械手臂)之影
響過大時。且期期盼得到趨近於零之定位誤差。
不適合於直角或大曲率之曲線軌跡。且期期盼得到很
小之超越誤差。
Chapter 4 Interpolator Design

4.1 Point-To-Point (Positioning) vs. Trajectory (Contouring)

(1) 各軸獨立定位控制 (點至點定位，Positioning)

(2) 軌跡路徑控制 (直線、圓弧、曲線)

4.2 Reference Pulse vs. Reference Word

(1) Reference pulses:
Interpolator產生pulses(squares)訊號，每一pulse為一(position) step。
常見於早期或小型之CNC machines。
適用於stepping motors或位置型electronic driver(接受數位脈波pulse訊號)。

(2) Reference words:
Interpolator產生數值訊號，servo controller處理的亦為數值訊號。
一般的CNC machines均採用此種方式。
適用於DC or AC motors及速度型或扭力型electronic driver(接受類比電壓電流訊號)。

4.3 Kinematics Transformation

針對多軸(4- or 5-axis)工具機與機械手臂
4.3.1 Direct Kinematics：多軸工具機與機械手臂之機構轉換

\[
\begin{align*}
\theta_1 & \rightarrow x \\
\theta_2 & \rightarrow y \\
\theta_3 & \rightarrow z \\
\theta_4 & \rightarrow \alpha \\
\theta_5 & \rightarrow \beta
\end{align*}
\]

4.3.2 Inverse Kinematics：為Interpolator主要功能之一

\[
\begin{align*}
x & \rightarrow \theta_1 \\
y & \rightarrow \theta_2 \\
z & \rightarrow \theta_3 \\
\alpha & \rightarrow \theta_4 \\
\beta & \rightarrow \theta_5
\end{align*}
\]

(1) Absolute Solution

\[
\begin{align*}
\theta_1 &= \theta_1(x, y, z, \alpha, \beta) \\
\theta_2 &= \theta_2(x, y, z, \alpha, \beta) \\
\theta_3 &= \theta_3(x, y, z, \alpha, \beta) \\
\theta_4 &= \theta_4(x, y, z, \alpha, \beta) \\
\theta_5 &= \theta_5(x, y, z, \alpha, \beta)
\end{align*}
\]

優點：解析解、正確解
缺點：解不唯一

(2) Incremental Solution

\[
\begin{align*}
\Delta \theta_1 &= \text{\textit{\text{\partial}}(x, y, z, \alpha, \beta)} \\
\Delta \theta_2 &= \text{\textit{\text{\partial}}(\theta_1, \theta_2, \theta_3, \theta_4, \theta_5)}^{-1} \\
\Delta \theta_3 &= \text{\textit{\text{\partial}}(x, y, z, \alpha, \beta)} \\
\Delta \theta_4 &= \text{\textit{\text{\partial}}(\theta_1, \theta_2, \theta_3, \theta_4, \theta_5)} \\
\Delta \theta_5 &= \text{\textit{\text{\partial}}(x, y, z, \alpha, \beta)}
\end{align*}
\]

優點：解唯一、可在工作座標系上控制
缺點：數值解、估計解
Chapter 5  System Implementation

5.1  Example for Machine Tool

三軸定位平台(X-Y-Z Table)

486PC

Interpolator

Servo Controller

PCL726
(6-channel DAC)

PCL833
(3-channel encoder board)

YSDC-1350P
(Driver)

speed
(voltage)

position
(pulses)

DC motor  Tachometer  Encoder

Guide Way
5.2 Example for Robotic Manipulator

五軸關節型機械手臂（Robot Manipulator）
Part II: Interpolator

[参考資料]


Chapter 1  Basic Interpolators for Lines and Arcs

一般的CNC machines均採用reference-word interpolators

1.1 Linear Interpolator

\[ x(k) = x(k-1) + fTt_x \]
\[ y(k) = y(k-1) + fTt_y \]

where \( f= \) feedrate, \( T= \) sampling time, \( (t_x, t_y)= \) unit vector along the line.

1.2 Circular Interpolator

\[ x(k) = x_c + r \cos[\theta(k)] \]
\[ y(k) = y_c + r \sin[\theta(k)] \]

where

\[ \cos[\theta(k)] = \cos[\theta(k-1) + \Delta \theta] = \cos[\theta(k-1)] \cos(\Delta \theta) - \sin[\theta(k-1)] \sin(\Delta \theta) \]
\[ \sin[\theta(k)] = \cos[\theta(k-1)] \sin(\Delta \theta) + \sin[\theta(k-1)] \cos(\Delta \theta) \]
\[ \Delta \theta = \frac{fT}{r} \]

Chapter 2  Conventional Curve Interpolators

References: Lo’s PhD thesis (Chapter 4, pp. 77~99)

Chapter 3  Another Method for Curve Interpolators

References: Lo’s paper “Feedback Interpolators for CNC Machine Tools”
Chapter 4 Interpolators for Multi-Axis Machine Tools and Manipulators

4.1 Multi-Axis Robotic Manipulator
Interpolator algorithm includes path interpolation and inverse-kinematics transformation

2D examples:

4.1.1 Absolute solution to inverse kinematics

\[
\begin{align*}
  x_e &= l_1 C_1 + l_2 C_{12} \\
  y_e &= l_1 S_1 + l_2 S_{12}
\end{align*}
\]

where \( C_1 = \cos(\theta_1), \ S_1 = \sin(\theta_1), \ C_{12} = \cos(\theta_1 + \theta_2), \ S_{12} = \sin(\theta_1 + \theta_2). \)

\[
\theta_1 = \tan^{-1}\left(\frac{y_e}{x_e}\right) - \cos^{-1}\left(\frac{l_1^2 + (x_e^2 + y_e^2) - l_2^2}{2l_1 \sqrt{x_e^2 + y_e^2}}\right)
\]

\[
\theta_2 = \pi - \cos^{-1}\left(\frac{l_1^2 + l_2^2 - (x_e^2 + y_e^2)}{2l_1 l_2}\right)
\]

4.1.2 Incremental solution to inverse kinematics

\[
\begin{bmatrix}
  \Delta \theta_1 \\
  \Delta \theta_2
\end{bmatrix} = \begin{bmatrix}
  \frac{\partial (x_e, y_e)}{\partial (\theta_1, \theta_2)}
\end{bmatrix}^{-1}
\begin{bmatrix}
  \Delta x \\
  \Delta y
\end{bmatrix}
\]

\[
\Rightarrow
\begin{bmatrix}
  \theta_1(k+1) \\
  \theta_2(k+1)
\end{bmatrix} = \begin{bmatrix}
  \theta_1(k) \\
  \theta_2(k)
\end{bmatrix} + \begin{bmatrix}
  -l_1 S_1 - l_2 S_{12} & -l_2 S_{12} \\
  l_1 C_1 + l_2 C_{12} & l_2 C_{12}
\end{bmatrix}^{-1}
\begin{bmatrix}
  x_e(k+1) \\
  y_e(k+1)
\end{bmatrix} - \begin{bmatrix}
  x_e(k) \\
  y_e(k)
\end{bmatrix}
\]

4.2 5-Axis Machine Tools

References: Lo’s PhD thesis (Chapter 4, pp. 99~106)
Chapter 5  Reference-Pulse Interpolators based DDA Techniques

5.1  Introduction to Digital Differential Analyzer (DDA)

\[ f_{out} = \frac{af_{in}}{2^N}, \quad N = \text{number of bits for the DDA} \]

5.2  Applications of DDA Interpolators

5.2.1  Linear interpolator

5.2.2  Circular interpolator
Part III: Servo Controller

[参考資料]


Chapter 1  Introduction to Control of Multi-Axis Machines

1.1  Process Model

Based on a second order type-1 motor-driven plant. Column friction is introduced. No hardware or computational delay is considered.

1.2  Computer Simulation and Experiment

References: Lo’s PhD thesis (Chapter 2, pp. 7~9) and NSC report (Chapter 2, pp. 5~8)

Chapter 2  Basic Methods of Servo Controllers

2.1  Basic Servo Control Methods

References: Lo’s PhD thesis (Chapter 2, pp. 22~27, Chapter 3, pp. 46~74)

2.1.1  Feedback Control
2.1.2  Feedforward Control
2.1.3  Cross-Coupling Control

2.2  Other Control Methods: variations/combinations/accessories

References: Lo’s PhD thesis (Chapter 3, pp. 60~62)

2.2.1  Friction Compensation

References: Lo’s paper (Real-Time Compensation for Friction Disturbance on Servo Control Table)

2.2.2  Flexible and Combinative Servo Control Systems

References: Lo’s NSC report (彈性化與組合化之伺服控制系統)
Chapter 3  Feedback Control of Multi-Axis Machine Tools

3.1  Control Scheme Based on Coordinate Transformation

3.1.1  3-axis machine tool

References: Lo’s paper (Three-Axis Contouring Control Based on A Trajectory Coordinate Basis)

3.1.2  5-axis machine tool

References: Lo’s paper (Control Scheme for a Five-Axis Machine Tool Based on Coordinate Transformation)

3.2  Combination of Servo Controller and Interpolator

References: Lo’s papers

(Feedback Interpolators for Three-Axis and Five-Axis Machining of Parametric Surfaces)
(Real-Time Generation and Control of Cutter Path for Five-Axis Machining)