Outline – Motion Control

- Sensors for Motion Control
  - Position Encoders
    - Incremental
    - Absolute
  - Encoder Interfacing
    - Decoding
- Control of Electric Motors
  - DC Motors
    - H-bridge Drivers
    - Relays
  - Stepper Motors
    - Example

Position Sensors

- Most motion control applications require accurate position and velocity measurements.
- *Position sensors*, which can provide velocity *estimates*, are of major interest in industrial automation:
  - Optical Position Encoders (= Digital Sensors)
    - Rotary
    - Linear (a.k.a. "Linear Scales")
  - Resolvers (= Analog Sensors)
    - Rotary
    - Linear (a.k.a. "Inductosyn™")

Rotary Optical Position Encoders

- Opto-electro-mechanical devices for measuring position:
  - Robust and reliable,
  - Provide digital outputs,
  - Absolute/incremental and rotary/linear versions are available,
  - Decoder circuits are needed to process encoder signals,
  - Cost goes up with the increasing resolution.

Structure of Incremental Encoders

- Encoders consist of a stripped disk in between a light source (LED) and a photo-detector.
- Depending on angular position of the disk, the stripes on the disk may either block or let the light pass through.
- Photo-detector emits a series of electrical pulses as it gets to detect light during the rotation of the disk.
- Note the spatial relationship between the disk's position and the pulse-stream being generated.
Structure (Cont’d)

• An encoder producing one set of pulses would not be useful since it could not indicate the direction of rotation.
• Almost all incremental encoders generate a second set of pulses that is 90° out of phase with the first one.
• Most rotary encoders produce an index pulse per revolution using a third detector (C) to indicate a reference position on the disk.

Decoders

• An interface circuit is necessary to derive position from incoming pulses.
  – 1X decoding (or interpolation):
    • (H to L) or (L to H) transitions in one channel are counted.
  – 2X decoding:
    • (H to L) or (L to H) transitions in both channels are counted.
    • 2 logic transitions per grid (period) are detected.
  – 4X decoding (the best one!):
    • (H to L) and (L to H) transitions in both channels are counted.
    • 4 logic transitions per period are detected.
    • Highest possible resolution is achieved in this case.

4X Decoding

• Counting transitions in both channels yields the angular position of its shaft: \( \theta = \frac{90° \times n}{N} \).
  – N is # of gratings on the disk.
  – n is the count value of transitions up to a particular time.
  – While counting transitions, one must keep track of the direction:
    • If forward, count up.
    • If reverse, count down.
  – Direction can be detected:
    • If A leads B \( \Rightarrow \) forward rotation.
    • If B leads A \( \Rightarrow \) backward rotation.

\( 360°/N \)
Resolution of Incremental Encoders

- Resolution is indicated by the number of gratings on the disk.
  - Number of pulses being generated in one channel per one revolution.
- Common resolutions are
  - 200, 500, 1000, 2000, 5000, 10000 pulses/rev.
- Cost goes up with the increasing resolution due to sophisticated manufacturing process:
  - Etching micro-gratings on a glass disk covered with chromium.

Courtesy of Heidenhain Corp.

Absolute Encoder (Cont’d)

- Major drawbacks of incremental encoder are
  - A decoder circuitry is needed.
  - In case of a power failure, the decoder will lose information on the current position.
- **Absolute encoders** are designed to tackle with these problems.
- Operating principle is similar to that of the incremental one:
  - has 8 to 16 photo-detectors
  - uses a coded disk generating a unique binary output per segment.
Absolute Encoder (Cont’d)

• Since each channel generates a particular digit of a binary number, it is customary to specify the resolution by bits (N):
  – 8-bit, 10-bit, 12-bit, ..., 16-bit
  – Angular resolution is $360^\circ / 2^N$.
• Absolute encoders are very expensive due to the complexity involved in the manufacturing process (photo-lithography).
  – Price goes exponentially up with the resolution.

Infinite Resolution Encoders

• Incremental encoders generating sinusoidal waveforms (instead of pulses) are referred to as *infinite resolution encoders*.
  – Name is a bit misleading!
• One can *interpolate* the magnitudes of two orthogonal sinusoidal waveforms (A and B) to find the exact location of shaft within one (grate) period.

Terminal Signals

• Following signals are available in a generic incremental encoder:
  • ChA: channel A
  • ~ChA: complement of channel A
  • ChB: channel B
  • ~ChB: complement (negation) of channel B
  • IX: index (sometimes called ChC)
  • ~IX: complement of index
  • $V_{dd}$: Supply voltage for the encoder (+5V)
    – Can be 3 to 24 Volts depending on the app.
  • $V_{ss}$: digital ground

Types of Encoder Interfaces

• Two types of encoder interfaces:
  – Single-ended
  – Differential
• Single-ended encoders are quite common:
  – Encoder and its interface are located in close proximity (~a few meters or less).
    • Noise (pick-up) is not a big issue.
  – $V_{ss}$ is connected to the digital ground.
  – ChA and ChB are directly employed as TTL inputs to the interface circuitry.
Encoder Interfaces (Cont’d)

- **Differential interfaces** are used when the encoder and its interface must be located far apart (like tens of meters).
  - Noise pick-up and degradation of transmitted signal become important issues.
  - “Balanced” digital data transmission is needed.
- In such interfaces, the potential difference between ChX and ~ChX (X: A or B) yields the desired logic signal:
  - ChX (wrt. to V_{ss}) ∈ {0, 2.5V}
  - ~ChX (wrt. to V_{ss}) ∈ {0, -2.5V}
- Differential line receivers (such as DS26C32) are commonly used for this purpose:
  - Accept differential encoder inputs
  - Yield corresponding TTL or CMOS logic outputs.

Processing Quadrature Signals

- Encoder “quadrature” signals must be processed to obtain position information in most cases.
  - Some DSPs and advanced microcontrollers have built-in quadrature encoder interfaces.
- There are various options to convert quadrature signals into position “counts”:
  - Custom digital circuits
  - Quadrature decoder ICs
  - Quadrature decoder / counter interface ICs

Custom Solutions

- A custom interface with 2X decoding can be designed with an XOR gate and a D flip/flop.
- Outputs of the circuit can be directly connected to the PIC18F4520:
  - CLK_{OUT} to Timer1 (RC1/T1CK1) for counting
  - DIR to (RB0/INT) for sign detection

Encoder-to-Counter Interface ICs*

- Produced by **US Digital** (cost ~ a few USD in quantity)
- Drives standard counters
  - Mostly used as inputs to “on-board” counters of microcontrollers.
- No external clock is required.
- Features
  - 1X or 4X interpolation mode
  - TTL/CMOS compatible I/O
  - Low power

Advanced ICs: HCTL-2032*

- Produced by Agilent Technologies (cost ~7 USD)
- Interfaces between encoder and microcontroller
  - Needs an external clock signal
- Has programmable interpolation modes:
  - 1X, 2X, or 4X
- Supports dual axis
- Features
  - 32-bit binary up/down counter
  - 8-bit tri-state interface
  - TTL/CMOS compatible I/O

Conventional DC Motor

- Stator of a DC motor is composed of two or more permanent magnet pole pieces.
- Rotor is composed of windings which are connected to a mechanical commutator. In this case the rotor has three pole pairs.
- Opposite polarities of the energized winding and the stator magnet attract and the rotor will rotate until it is aligned with the stator.
- Just as the rotor reaches alignment, the brushes move across the commutator contacts and energize the next winding.
- A spark shows when the brushes switch to the next winding.

Operating Modes of DC Motor

- In motor mode, the machine drives the “load” and needs energy from the supply.
- In generator mode, the “load-side” drives the machine and it generates power.

“Forward Motor” Control

- Electronically-controlled (unidirectional) switch is turned on/off rapidly.
  - Pulse width modulation
- Desired (average) voltage at the terminals of DC motor is obtained via controlling switching times:
  \[
  V_a = V_{DC} \frac{T_d}{T_p} = V_{DC} \cdot d
  \]
  where \( T_p \) is PWM period (constant) and \( T_d/T_p = d \) is called duty cycle.
Forward Motor Control (Cont’d)

Mode 1:
- When S₁ is turned off, iₘ flowing through the motor cannot be cut off immediately.
  - It must flow somewhere!
- “clamp” diode allows current flow in Mode 2:
  - Lₘ drives a decaying current.
- If D₁ isn’t in place, a very large voltage will build up across S₁ and blow it up.

Mode 2:

Four-Quadrant Motor Control

- “H” bridge is used to operate the motor in four quadrants.
- Driver is composed of two half-bridges.
- Switches in a half-bridge cannot turned at the same time.
  - causes short-circuit.
  - If one of the switches is turned, the other must be off.

Forward Motor

Mode 1:
- To go forward,
  - S₂ is fully turned on;
  - PWM and ~PWM (inverted PWM) signals are applied to S₂ and S₁ respectively.
- Unidirectional switch S₁ can carry current only in the indicated direction.

Mode 2:

Reverse Motor

Mode 1:
- To go reverse,
  - S₁ is fully turned on;
  - PWM and ~PWM signals are applied to S₄ and S₃ respectively.

Mode 2:
Building H-bridge

- Commercial Motor Drivers
  - Include all bells and whistles!
- Custom Solutions (high-power)
  - Switches: Power MOSFETs, IGBT
  - Need gate drivers and signal isolation barriers.
- Bridge ICs (up to a few-hundred [W])
  - LMD 18200
  - L298
- For driving small DC motors,
  - L293D
  - ULN 2003A

LMD 18200*

- Ideal for driving DC and stepper motors,
- Delivers up to 3A continuous output
  - Peak current of 6A
- Operates at supply voltages up to 55V,
- Accepts TTL and CMOS compatible inputs,
  - Internal charge pump
- Quite expensive: 20 USD.

L298: Dual H-bridge Driver*

- Constitutes two H-bridges
  - Requires clamp diodes
- Supply voltage up to 46V
- Maximum current is 4A
- Over-temperature protection
- Accepts TTL inputs

L293D: Four Half-bridge Drivers*

- L293 includes 4 Half-bridge drivers.
  - Can drive two bidirectional DC motors.
- L293D has clamp (freewheeling) diodes.
- Wide supply-voltage range: 4.5 V to 36 V
- Output current for L293D is 0.6A/channel
  - 1.2A peak
- Thermal shutdown

[*] Courtesy of National Semiconductors.
[*] Courtesy of ST Microelectronics.
[*] Courtesy of Texas Instruments.
Electromagnetic Relays

- Relays are electromagnets connected to mechanical switches.
  - When the electromagnets are energized, the switches are pulled into contact.
  - Hence, the corresponding circuit is powered up.
- Relays allow the control of high-power devices.
  - Small power is sufficient to energize electromagnets in relays.
  - Suitable for on/off control of slow devices:
    - Pump (AC/DC) motors, solenoids
    - Heaters, lamps, etc.
  - If compared to solid-state switches, relays are more susceptible to malfunction.

Simple On/Off Control

- Most microcontrollers cannot source/sink in sufficient current to trigger relays.
- General purpose BJTs (2N2222, 2N3904, BC337, etc) or ULN2003A (Transistor Array) are utilized for this purpose.

Stepper Motors

- Stepper Motors
  - Variable Reluctance (VR)
    - Rotor saliency
  - Permanent Magnet (PM)
    - Magnets on rotor
  - Hybrid Motors
    - Relies on both rotor saliency and magnets
- Each pulse moves rotor by a discrete angle (i.e. "step angle").
- Counting pulses tells how far motor has turned without actually measuring (no feedback!).

Advantages / Disadvantages

- Low cost
- Simple and rugged
- Very reliable
- Maintenance free
- No sensors needed
- Widely accepted in industry
- Resonance effects are dominant
- Rough performance at low speed
- Open-loop operation
- Consume power even at no load
(Simplified) Full-Step Operation

- Rotor of a PM stepper motor consists of a permanent magnet:
  - Stator has a number of windings.
- Just as the rotor aligns with one of the stator poles, the second phase is energized.
- The two phases alternate on and off to create motion.
- There are four steps.

(Simplified) Half-Step Operation

- Commutation sequence has eight steps instead of four.
- Main difference is that the second phase is turned on before the first one is turned off.
- Sometimes, both phases are energized at the same time.
- During the half-steps, the rotor is held in between the two full-step positions.
- A half-step motor has twice the resolution of a full-step motor.
  - Very popular due to this reason.

Winding Connections

- Unipolar (5-wire):
  - Current flows through a coil only in one direction.
- Bipolar (4-wire):
  - Current flowing through a winding changes direction during the operation.
- Unipolar (6-wire):
  - Current flows through a coil only in one direction.
Actual Stepper Motor*

- Stator of a real motor constitutes more coils (typically 8).
- Individual coils are interconnected to form only two windings:
  - one connects coils A, C, E, and G:
    - A and C have S-polarity
    - E and G have N-polarity
  - one connects coils B, D, F, and H:
    - B and D have S-polarity
    - F and H have N-polarity

Chapter 11 ME 534 [*] Courtesy of Microchip. 42

Stepper-Motor Animations*

Full-step:

Half-step:

Chapter 11 ME 534 [*] Courtesy of Motorola, Inc. 43

L297: Stepper Motor Controller*

- Produced by STMicroelectronics
- To be used in conjunction with L298
- Half/full step modes with direction control input.
- Switch-mode load current regulation

Chapter 11 ME 534 [*] Courtesy of ST Microelectronics. 44

Stepper Motor Drive with L293*

- Half-bridge pair of L293 is utilized to drive a phase winding of a bipolar stepper motor.
  - Depending on control input (Control A or B), current flows in one way or another.
- No external (clamp) diodes are needed if L293D is employed.

Chapter 11 ME 534 [*] Courtesy of ST Microelectronics. 45
Let us develop a C program for a PICmicro controlling the (unipolar) stepper motor shown.

- 20kΩ pot. is used to adjust the speed. When the voltage on AN0 is
  - 5V → motor rotates CW direction at its max. speed.
  - 2.5V → motor is off.
  - 0V → motor rotates CCW direction at its max. speed.

- LED indicates the direction of motion.
- SSD shows speed as a hex number (0: min; F: max)
- Here, ULN2003A (transistor array) serves as "electrically controlled switch.
  - When 5V is applied by PICmicro, it conducts current (up to 1A).

- 20kΩ pot. is used to adjust the speed.

- LED indicates the direction of motion.
- SSD shows speed as a hex number (0: min; F: max)
- Here, ULN2003A (transistor array) serves as "electrically controlled switch.
  - When 5V is applied by PICmicro, it conducts current (up to 1A).

Chapter 11  ME 534  46

C Program: Half-step

```c
#include <18F4520.h>
#define ADC=10
#define fuse HS,NOWDT,NOPROTECT,NOLVP
#define delay(clock=2000000)
#define rs232(baud=19200, xmit=PIN_C6, rcv=PIN_C7)
#define fast_io(B)
#define byte PORTB = 0xF81
#define byte PORTD = 0xF83
#define bit LED = PORTD.2

void ss_disp(int num) { /* Seven segment display routine */
byte const SSData[16] = {238,130,220,214,178,118,126,226,  
                        254,246,250,62,28,158,124,120};
if(num < 16) {
    output_b(SSData[num]);
 }
}
```

Chapter 11  ME 534  47

C Program (Cont’d)

```c
void main() {

    byte const step[8] = {192,64,96,32,48,16,144,128}; /* Half-step sequence */
    byte temp = 0;
    long adval;
    int i = 0;

    set_tris_b(0); /* Set up digital I/O pins */
    set_tris_d(3);
    PORTB = 0; PORTD = 0;

    setup_adc_ports(AN0_TO_AN3); /* Set ADC */
    setup_adc(ADC_CLOCK_INTERNAL);
    set_adc_channel(2);
```
C Program (Cont’d)

```c
while(TRUE) {
    delay_us(200);
    adval = read_ADC()>>3;
    if (adval>60 && adval<68) { /* Motor is off */
        ssDisp(0); PORTD = 0;
    } else if(adval>=68) { /* CW direction */
        ssDisp((adval>>2)-16);
        adval = 132 - adval;
        if (++i>7) i = 0; temp = (PORTD&15)+step[i];
        PORTD = temp; LED = 1; delay_ms(adval);
    } else { /* CCW Direction */
        ssDisp(16-(adval>>2));
        if (--i<0) i = 7; temp = (PORTD&15)+step[i];
        PORTD = temp; delay_ms(adval);
    }
}
```

Chapter 11 ME 534 50