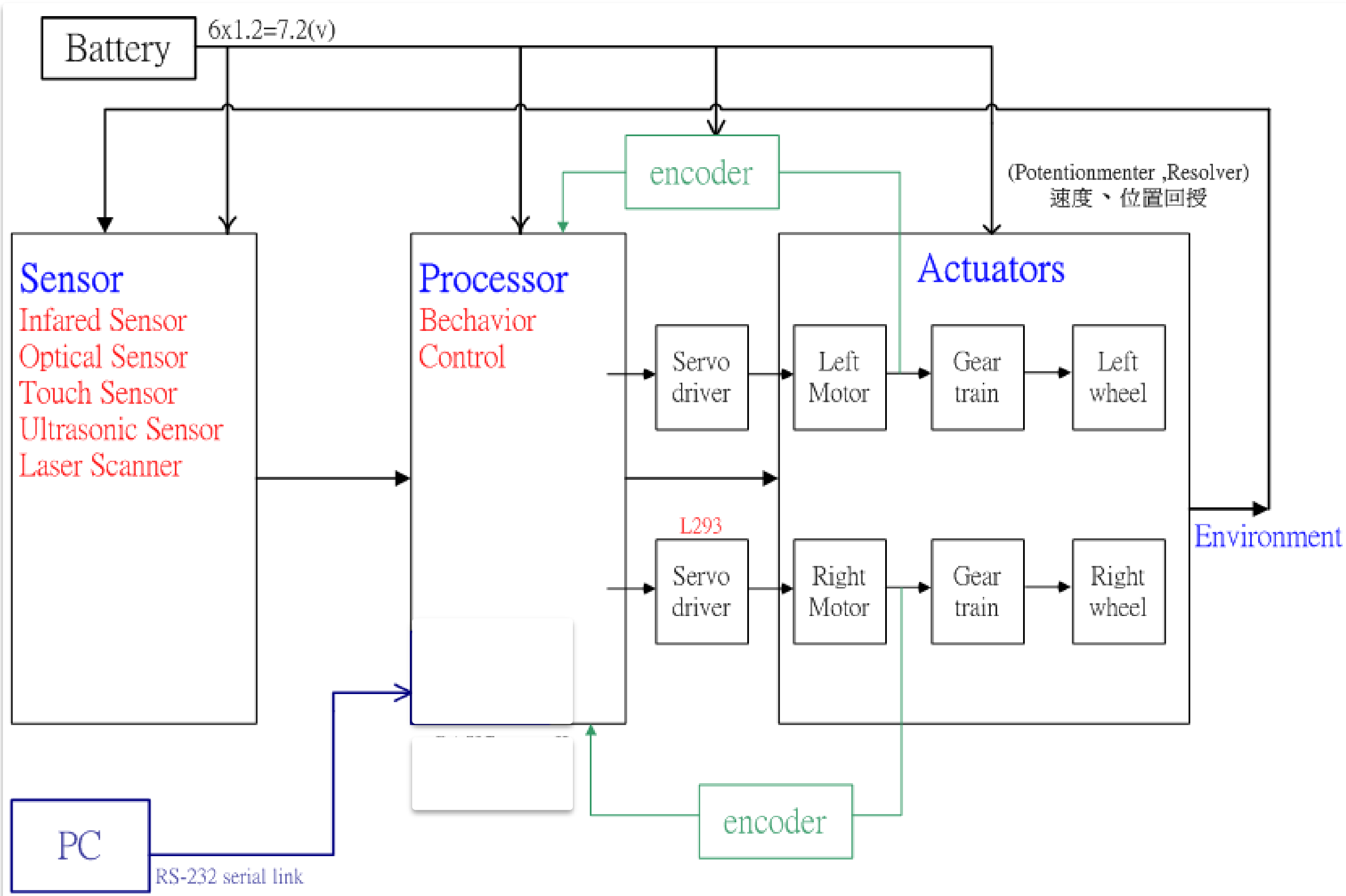
Mobile Robots
(EECN30169/535307)

Lec. 3 Motion Control of Mobile Robots

2022/9/30

Control Architecture of a Mobile Robot

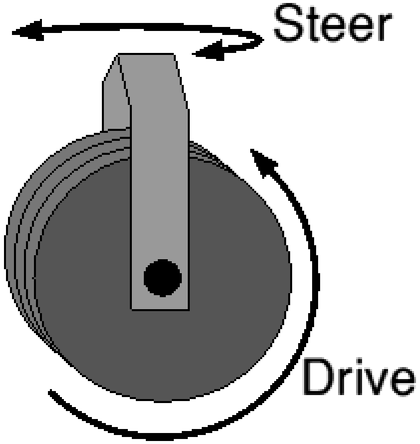


Mobile Platform

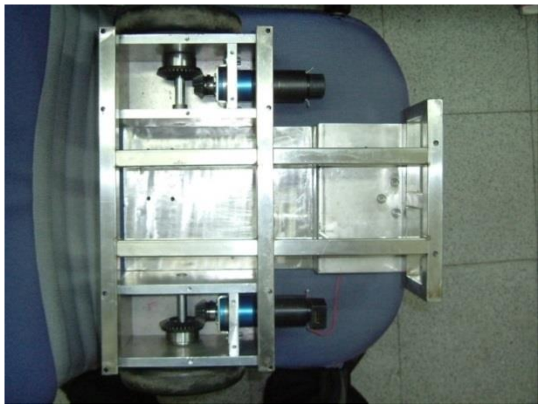
- Mobile robot→
  Robot body structure
  (Motion platform + Wheels)
  + Propelling
  (Batteries + Motors+ Servo drivers)
  + Functionalities
  (Functionalities for task execution)
- Electrical motors are the most used actuators.

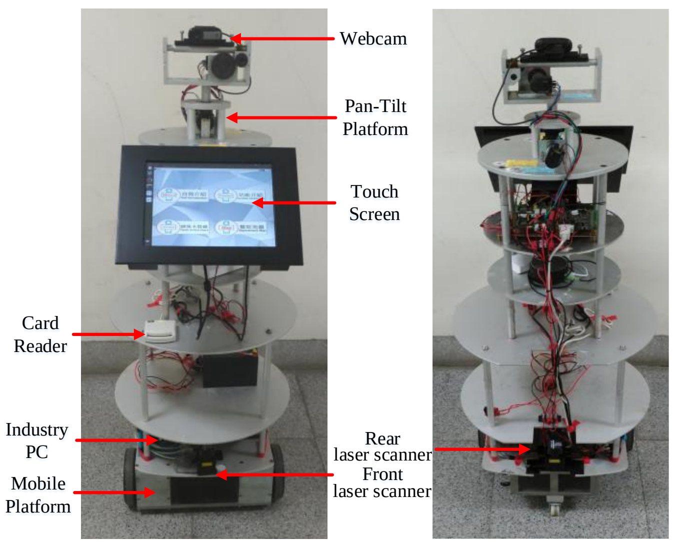
Front drive and steer system

- Drive and steer on the same wheel, similar to cars
- One motor drives, another motor steers
- Dead reckoning on the other two passive wheels. Because these two wheels are not powered, slippage is less likely to occur.
- 2 DOF motion on a plane.



Two independent-drive wheels (differential drive)





Advantages:

1. Easy to construct
2. Can spin at the spot
3. Better to work with a path planner(using visibility graph)

Drawbacks:

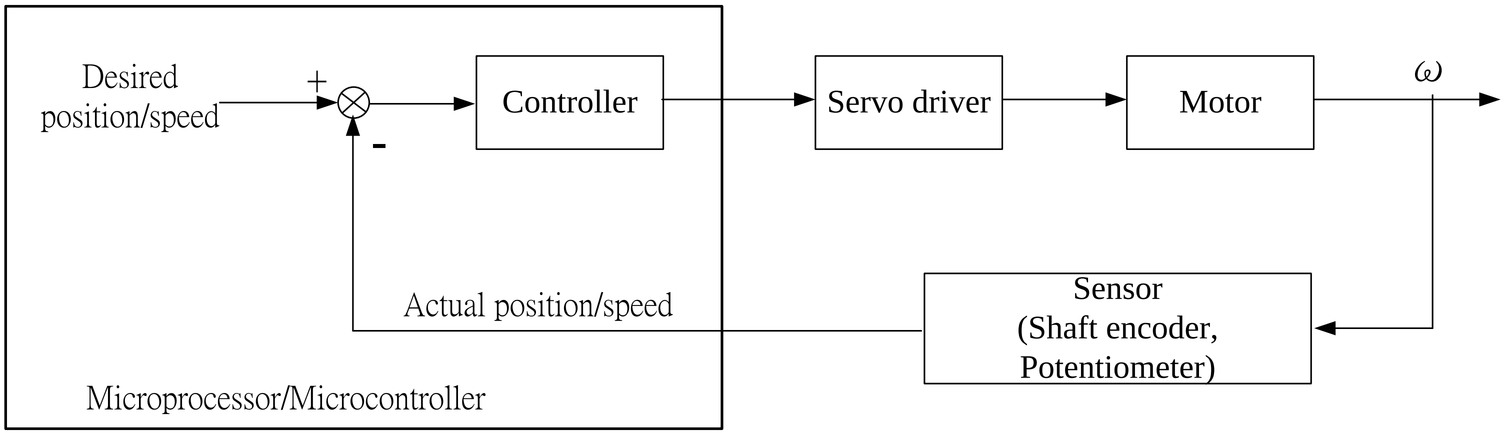
1. Problem to move in a straight line
2. Slippage errors
3. Need to coupling between two drive wheels

DC Motors

DC Motors

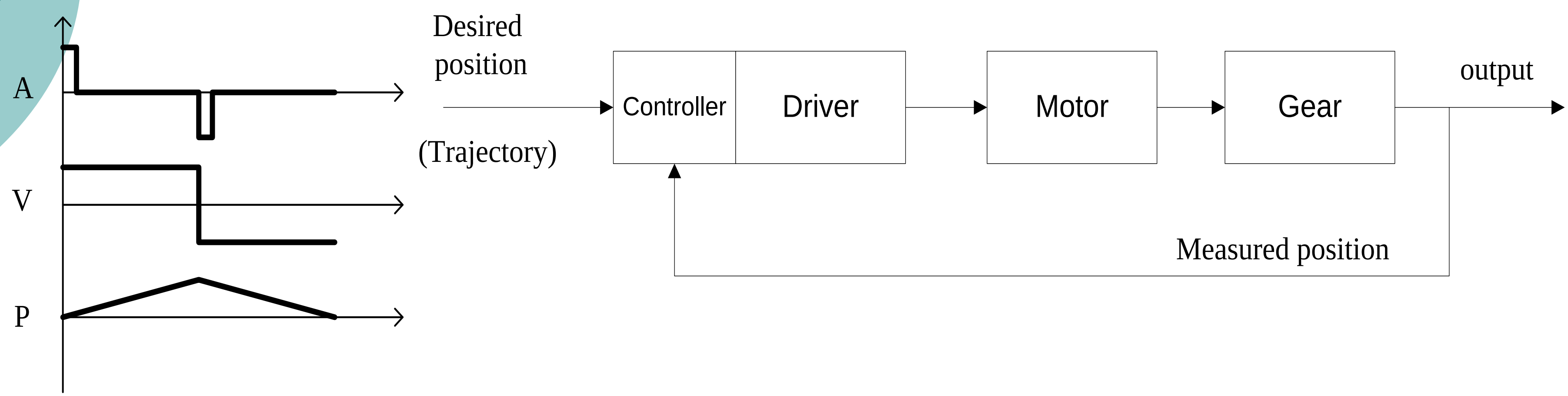
- DC motor fundamentals
- Motor model and characteristics
- Selection of DC motors
- Servo drivers: PWM+L293 (Amplifiers)
- Speed control
- Design using motion controller chips : LM629, HCTL 1100, …

Servo Control Loop



AC motor (higher speed, AC voltage supply)
DC motor (lower speed, DC voltage supply): small, low cost, reasonable efficient, easy to use
Rotor: loops of wire mounted on a rotating shaft (armature)
Stator: permanent magnetic

Trajectories of a Servo Motor

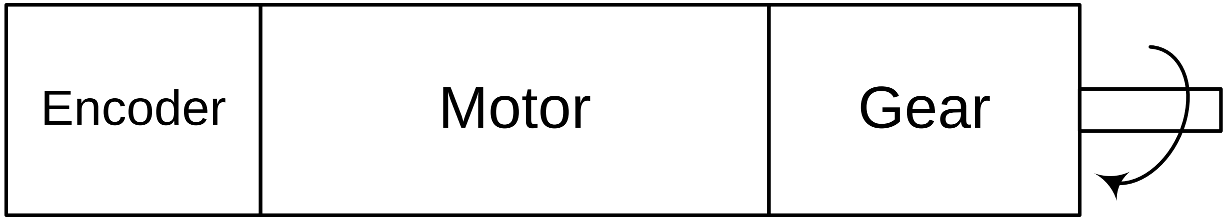


The word servo refers to the system's capability to self-regulate its behavior, i.e. it measures its position and compensate for external loads when responding to a control signal (trajectory).

Gear Head Motors

- DC motors: normally run at high speed and low torque

  → Reduction gears are used to increase torque and reduce speed.



A Gear Head Motor

Rotational Speed and Direction

- Most DC motors have two electric terminals.
- Applying voltage across these terminals causes the motors to spin in one direction.
- While reversing polarity voltage will cause the motor to spin in other direction.
- Polarity of the voltage determines the rotation direction; amplitude of the voltage determines motor speed.

DC Motor Fundamentals

- When provided with a constant voltage, a motor draw current proportional to how much work it is doing.
- When there is no resistance to its rotation, the motor draws the least amount of current.
- When there is so much resistance as to cause the motor to stall, it draws the maximum amount of current (stall current).
- The more current going through a motor, the more rotation force (torque) is produced at the motor's shaft.

Current, Torque and Power

- Stall current:

  The maximum amount of current that a motor can draw at its specified voltage.
- Stall torque:

  The amount of rotation force produced when the motor is stalled at its recommended operation voltage, drawing the maximum stall current at this voltage.
- Power:

  Rotational velocity x torque

Unit of Torque

$$T : \text{torque} \qquad\qquad \text{unit} : \begin{cases} \text{N - m} \\ \text{gf - cm} \\ \text{lb - in} \\ \text{oz - in} \end{cases}$$

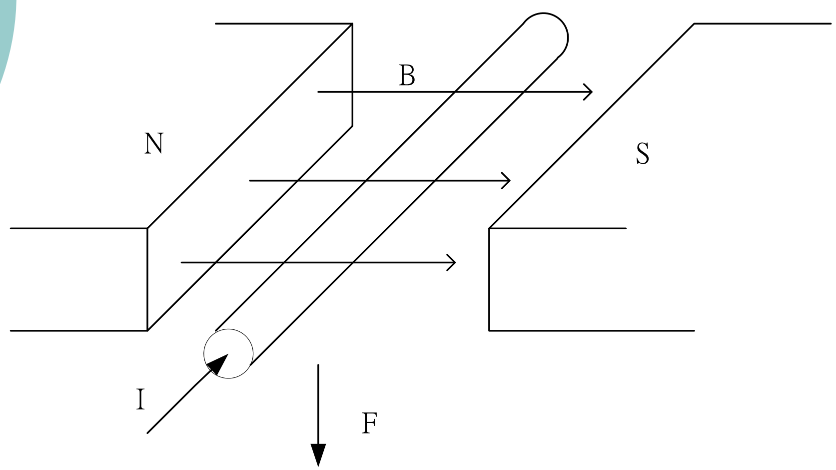
$$mNm = 10^{-3}\, Nm$$

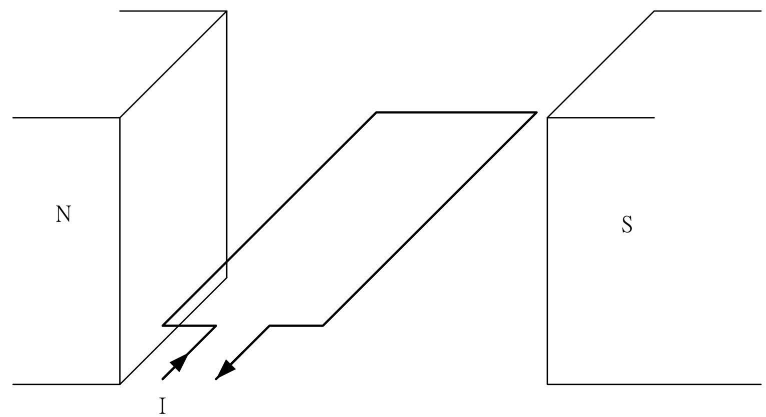
$$1lb - in = 0.113\, Nm$$

$$1oz - in = 7.06\, mNm$$

$$1lb = 4.45\, N = 16oz, \ 1in = 2.54cm$$

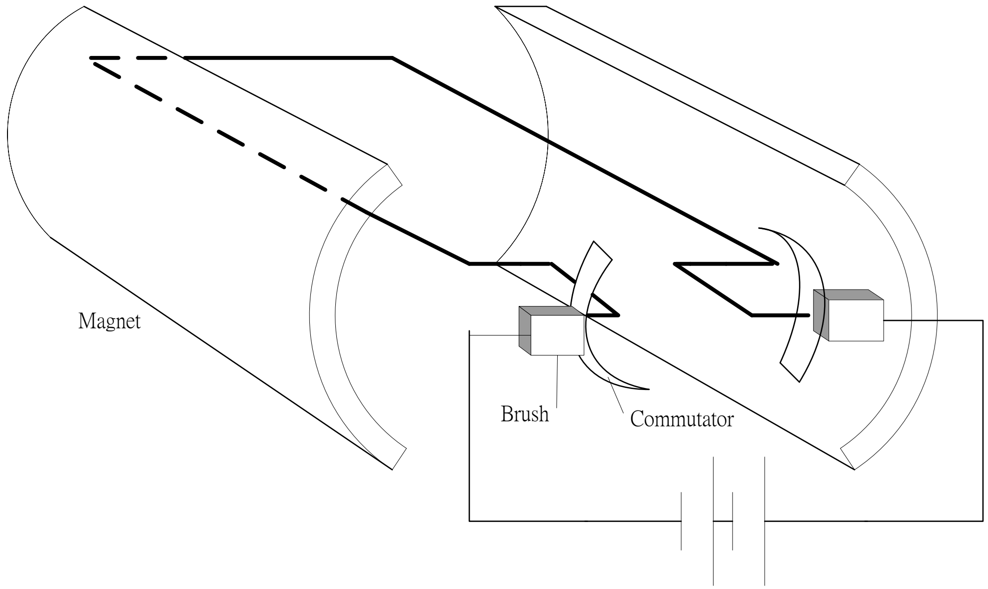
Lorentz Force Law





Current-carrying conductors placed in magnetic field creates forces.

Commutation of DC Motors



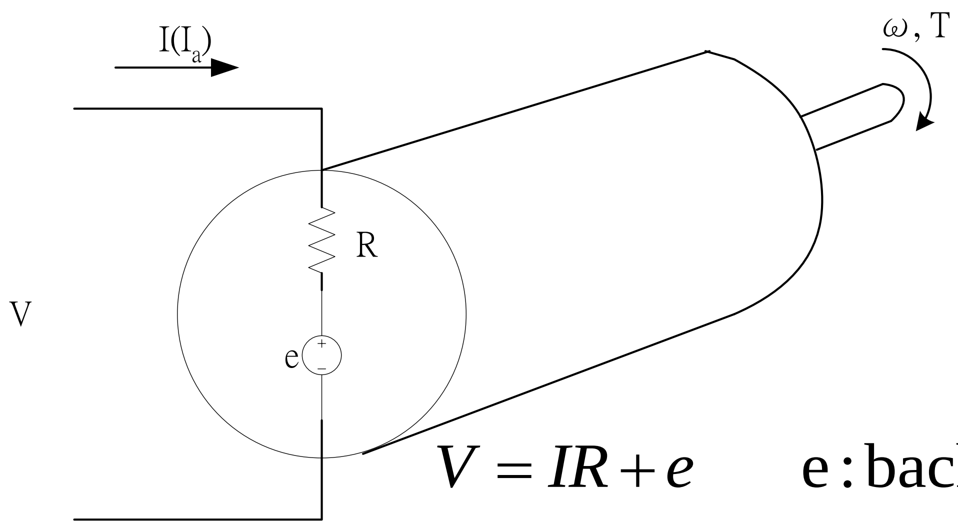
Brush type:
If the DC current is commutated mechanically with brushes, the commutator segments at the ends of the rotating rotor coil physically slides against the stationary brushes that are connected to the motors terminals on the outside of the case.

Brushless Type:

- If the DC motor current is converted into AC current in the rotor electronically, with position sensors and a microprocessor controller, then no brushes are needed.
- Advantages: Longer life, finer control
- Disadvantages: More expensive, controller circuitry

DC Motor Characteristics

- The armature (rotor) coil is essentially an inductor with a resistance R. As armature rotates, the brushes impart alternating current in coil.
- The induced voltage opposes applied voltage(Lentz law).



$$V = IR + e \qquad \mathrm{e : back\ emf\ (induced\ voltage)}$$

$$e = k_e \omega \qquad \mathrm{k_e : back\text{-}emf\ constant}$$

Induced Voltage (back-emf)

- The faster the motor turns, the more of the current switches direction and so the larger the induced voltage.
- → limit the current through the resistance R (through the coil)
- → limit the torque of the motor.
- → $\omega\uparrow$, T $\downarrow$

Stall Current

- Negative feedback of back-emf causes motor to reach steady-state operating point of speed and voltage as determined by applied voltage and load.
- Note: $I_{max} = \frac{V}{R}$ occurs when ω= 0, this

is the starting current or stall current (Is).

Delivered Mechanical Power

$$V = IR + k_e \omega$$

$$T = k_t I, \quad k_t : \text{torque constant}$$

$$P_m = P_e - I^2 R$$

$$T\omega = VI - I^2 R$$

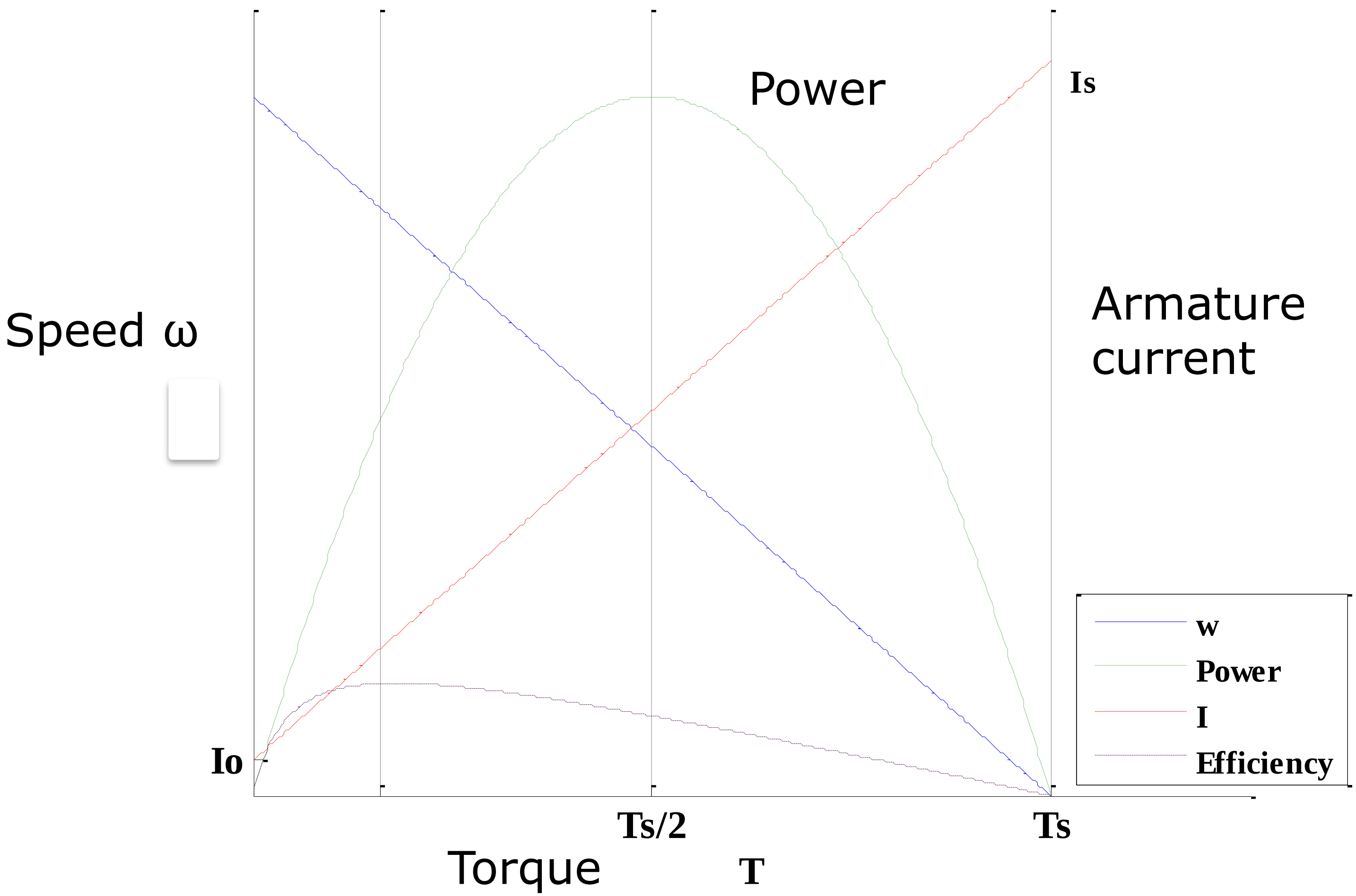
$$(k_t I)\omega = (IR + k_e \omega)I - I^2 R \Rightarrow k_t = k_e = k$$

$$\omega = \frac{V - IR}{k} = \frac{-(\frac{T}{k})R}{k} + \frac{V}{k} = -\frac{TR}{k^2} + \frac{V}{k}$$

$$P_m = T\omega = \frac{-RT^2}{k^2} + \frac{V}{k}T$$

Mechanical power has quadratic dependence on torque.

Speed-Torque Curve



No Load Speed

- No load speed : the speed, at a given voltage, at which the torque is 0 (T = 0)

$$\omega_{max} = \frac{V}{k}$$

- No load current: at no load condition, I_0 is required to overcome motor friction and windage.

Stall Torque

- Maximum torque when motor stalled ($\omega = 0$, emf = 0),

$$I_s = I_{\max} = \frac{V}{R}, T_s = kI = \frac{Vk}{R}$$

occurs at $\omega = 0, emf = 0$

Torque at Maximum Power:

$$\frac{dP_m}{dT} = 0 \Rightarrow \frac{-2R}{k^2}T + \frac{V}{k} = 0$$

$$\Rightarrow T = \frac{kV}{2R} = \frac{1}{2}T_s = \frac{1}{2}T_{\max}$$

ω at max power: substitute $T = \dfrac{kV}{2R}$ $\quad \omega = -\dfrac{R}{k^2}T + \dfrac{V}{k}$

$$\Rightarrow \omega = -\frac{R}{k^2}\left(\frac{kV}{2R}\right) + \frac{V}{k} = \frac{V}{2k} = \frac{1}{2}\omega_{\max}$$

ω_{max}: ω at T=0

Maximum Power

$$P_{\max} = \left(\frac{1}{2}T_{\max}\right)\left(\frac{1}{2}\omega_{\max}\right) = \frac{1}{4}T_{\max}\omega_{\max}$$

Efficiency: The ratio of mechanical power output to electrical power input.

$$P_m = \eta P_e, \eta_{\max} = \left(1 - \sqrt{\frac{I_o}{I_s}}\right)^2$$

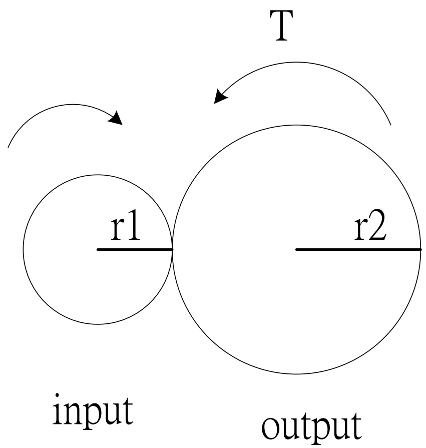
I_0: No load current

I_s: Stall current

Max efficiency ≠ Max power (We would like to drive the motor at max efficiency.)

Select an oversized motor so that it can run at an efficient operation point while supply enough torque.

Gearing



$$T = F \cdot r$$

From conservation of work:

$$W = T \cdot (\text{angular displacement})$$

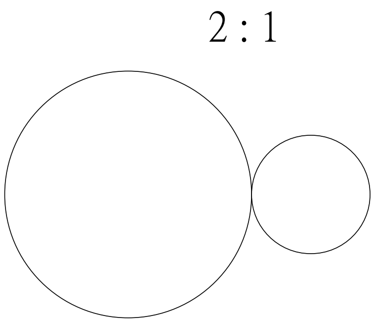
$$T_{large} \times 360^{\circ} = T_{small} \times 1080^{\circ}$$

$$\Rightarrow \frac{T_{large}}{T_{small}} = \frac{1080^{\circ}}{360^{\circ}} = 3$$

For example: $\frac{r_1}{r_2} = \frac{1}{3}$

Worm gear can attain large gear down in a small space.
➔ use screw mechanism to generate motion at right angle to the shaft.

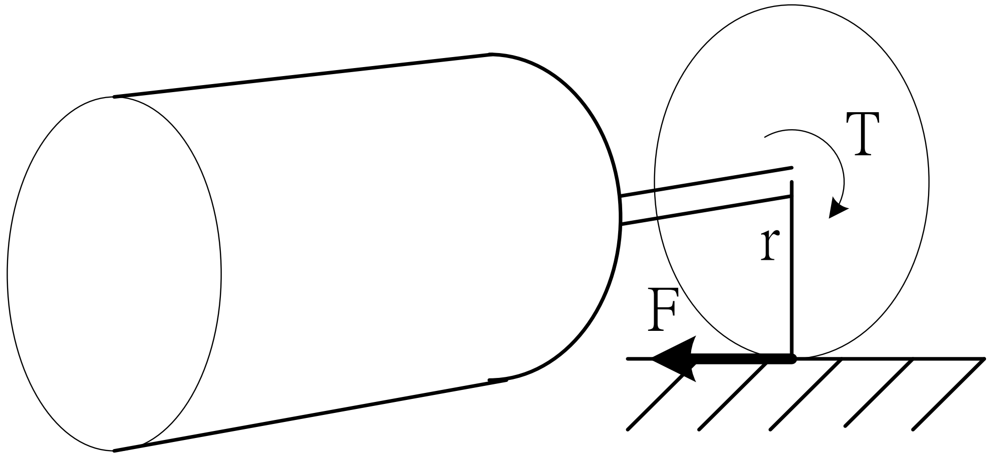
Example 1



- Gear factor = 2
- → No load speed = Double, while half the stall torque.
- Power maintains constant → (but more loss due to gearing)

$$T_1 \times \frac{360^\circ}{s} = T_2 \times \frac{720^\circ}{s} \Rightarrow T_2 = \frac{1}{2} T_1$$

Friction Force



$$F = F_N \times \mu$$

$$F \times r = T$$

F_N : Normal force

μ : Friction coefficient

Example 2

- A DC motor : internal resistance R=2Ω, running at full load with a 7.2V battery, a current of 500mA is drawn.

(a) e, back emf ?

$$V = e + iR$$

$$7.2 = e + 0.5 \times 2 \Rightarrow e = 6.2(V)$$

(b) power delivered to the motor (P_e)

$$P_e = i \cdot V = 0.5 \cdot 7.2 = 3.6(W)$$

Example 2 (continued)

(c). power dissipation in motor:

$$P_d = i^2 R = 0.5^2 \times 2 = 0.5(W)$$

(d) what is the mechanical power developed?

$$3.6 - 0.5 = 3.1(W)$$

$$\eta = \frac{3.1}{3.6} \times 100\% = 86\%$$

$$(emf \cdot i = 6.2 \times 0.5 = 3.1W)$$

Selection of DC Motors: an Example

Application data

Parameter	Symbol	Unit	Value
Required torque	M	mNm	3
Required speed	N	RPM	5500
Available supply voltage	U	V_{DC}	20
Available supply current	I	A	0.5
Available space	Φ	mm	(Φ)25*(L)50

Power Required (the motor is expected to deliver)

$$P_r = T\omega = M \cdot n \frac{2\pi}{60 \times 1000} = 3.5500 \frac{\pi}{30 x 1000} = 1.73W$$

A motor selected will deliver at least 1.5 to 2 times the power required.

$$P_{2\cdot\max} \geq 2P_r, U_N \geq U$$

Series 2233T024S: $U_N = 24V, P_{2\max} = 2.47W$

For a Smaller Supply Voltage

- Should the available supply voltage be lower than the nominal voltage of the selected DC motor, the $P_{2,\max}$ from the motor catalogue should be corrected:

$$P_{2\max} = \frac{R}{4}\left(\frac{U}{R} - I_o\right)^2 \Rightarrow P_{2\max}(20V) = \frac{57}{4}\left(\frac{20}{57} - 0.005\right)^2 = 1.7W$$

R: terminal resistance

I_0: no-load current

Optimizing the Pre-selection:

1). The required speed (n) has to be higher than half the no-load speed ($\omega_{\max}$) at nominal voltage.

$$n \geq \frac{\omega_o}{2}$$

2). The load torque (M) has to be less than half the stall torque (Ts)

$$M \leq \frac{T_s}{2}$$

Example 3

From data sheet,

ω_0 =8800 rpm, Ts=10.70mNm

$$\begin{cases} n(5500\,rmp) \geq \dfrac{\omega_o}{2}(\dfrac{8800}{2} = 4400\,rpm) \\ M(3) < \dfrac{T_s}{2}(\dfrac{10.7}{2} = 5.35\,mNm) \end{cases}$$

Performance Characteristics at Normal Voltage (24VDC)

- Stall current $I_0 = \frac{U_n}{R} = \frac{24}{57} = 0.421A$

Torque at max efficiency:

$$T_{opt} = \sqrt{T_s \cdot T_R}$$
$$= \sqrt{10.7 * 0.13} = 1.18mNm$$

T_R : friction torque

Main Parameters at 20VDC

1)No-load speed at 20V DC

$$n_0 = \frac{U - (I_0 x R)}{k_E} x1000 = \frac{20 - (0.005 x 57)}{2.690} x1000 = 7328\, rpm$$

2) Stall current

$$I_H = \frac{U}{R} = \frac{20}{57} = 0.351 A$$

3) Stall torque

$$T_H = K_m (I_H - I_o)$$

$$T_H = (25.70 \frac{mNm}{A})(0.351 - 0.005) = 8.91 mNm$$

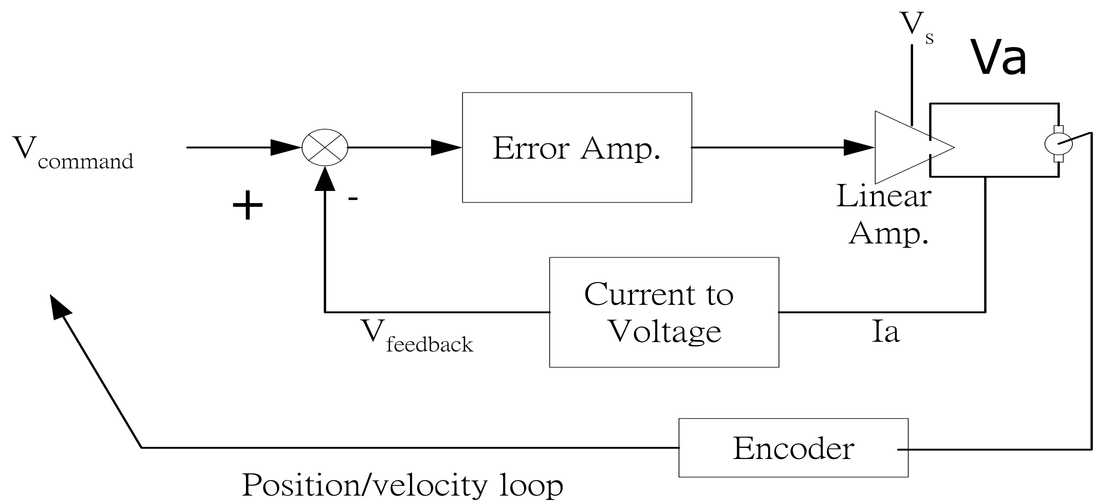
Output Power:

$$P_{2,\max} = \frac{R}{4}\left(\frac{U_N}{R} - I_0\right)^2$$

$$P_{2,\max}(20V) = \frac{57}{4}\left(\frac{20}{57} - 0.005\right)^2 = 1.7W$$

Servo Drivers

Servo Drivers: Linear Servo Amplifier



$V_{feedback}$: Sensing the armature current and converting to an analog voltage signal;
a voltage representation of the actual current.

$V_{command}$:A voltage representation of the desired motor current.

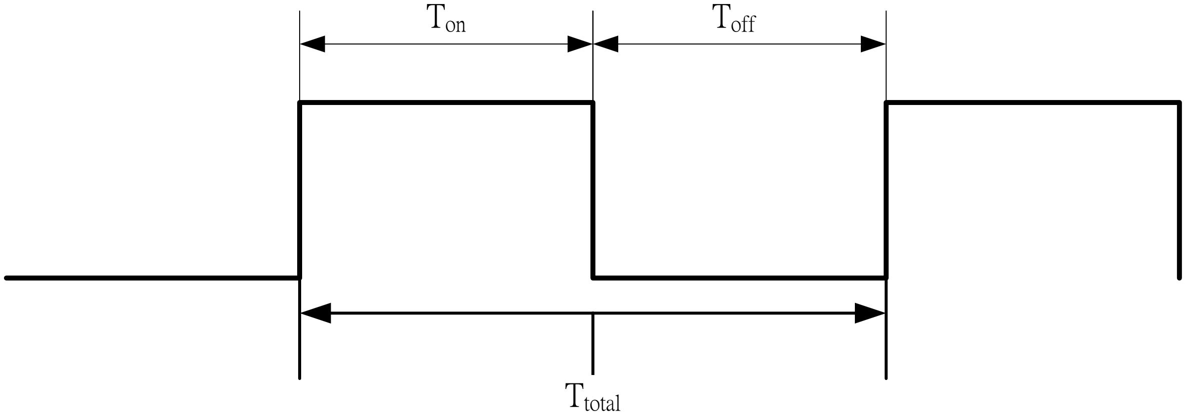
Error amplifier: Works as a controller,
responsible for the stability and performance

Problem of Linear Servo Drivers

- The primary disadvantage of linear servo amplifiers is excessive power dissipation.
- Servo amplifier is in series with the motor, and the armature current I flows through the amplifier.
- There is a difference between the power supply voltage Vs and the amplifier's output voltage Va

$$P_{dissipation} = I \times (Vs - Va)$$

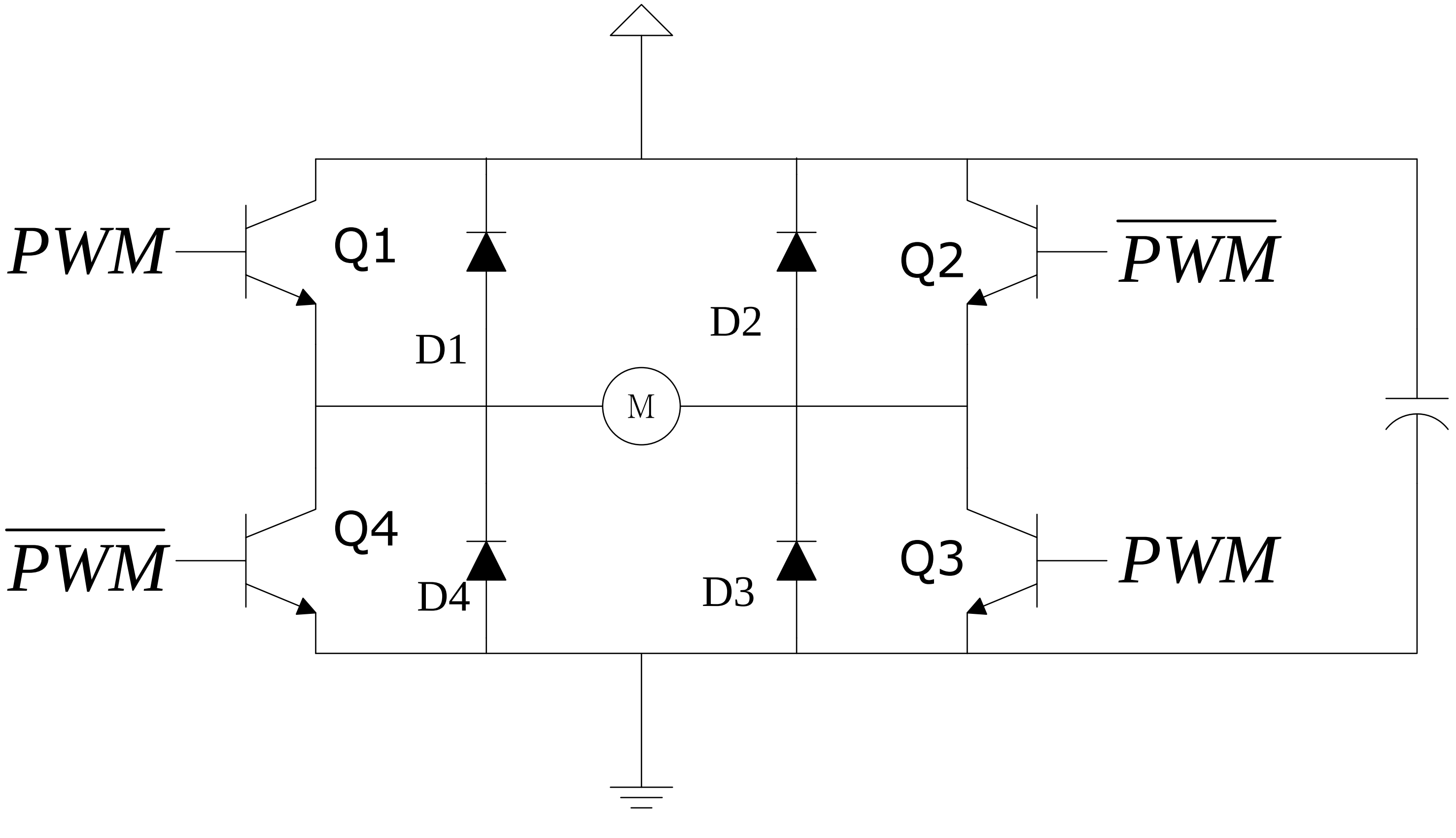
Duty Cycle



T_{total} = Cycle time (Typical PWM frequency is 2K to 30K Hz, 1K Hz for BS2)

Duty cycle=$T_{on}/(T_{on} + T_{off})$

H-bridge Power Stage:



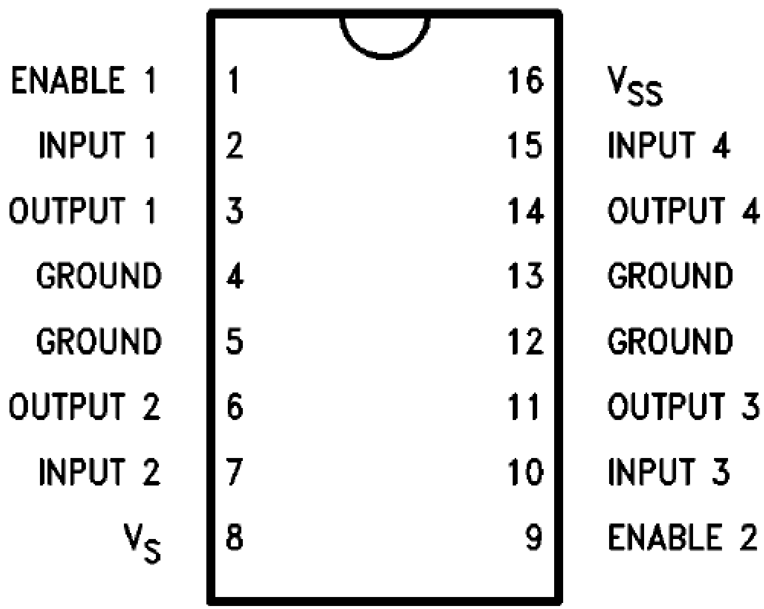
Working Principle of PWM(1/2)

- The transistors are always operated as switches, they are either fully on (saturated) or fully off (Cut-off). At any time, either Q1, Q3 or Q2, Q4 are on.
- Ideally, the transistors are either in a state of current and no voltage or voltage and no current. This gives us zero-power operation of PWM, or a dissipationless power stage.

Working Principle of PWM (2/2)

- Ideally, the transistors are either in a state of current and no voltage or voltage and no current. This gives us zero-power operation of PWM, or a dissipationless power stage.
- Switching frequency of PWM ≒2KHz ~30KHz is well above motor's electrical bandwidth. So the motor's inductance can act as an effective filter to the supplied voltage pulse train.

H-Bridge Driver IC L293 and L293D



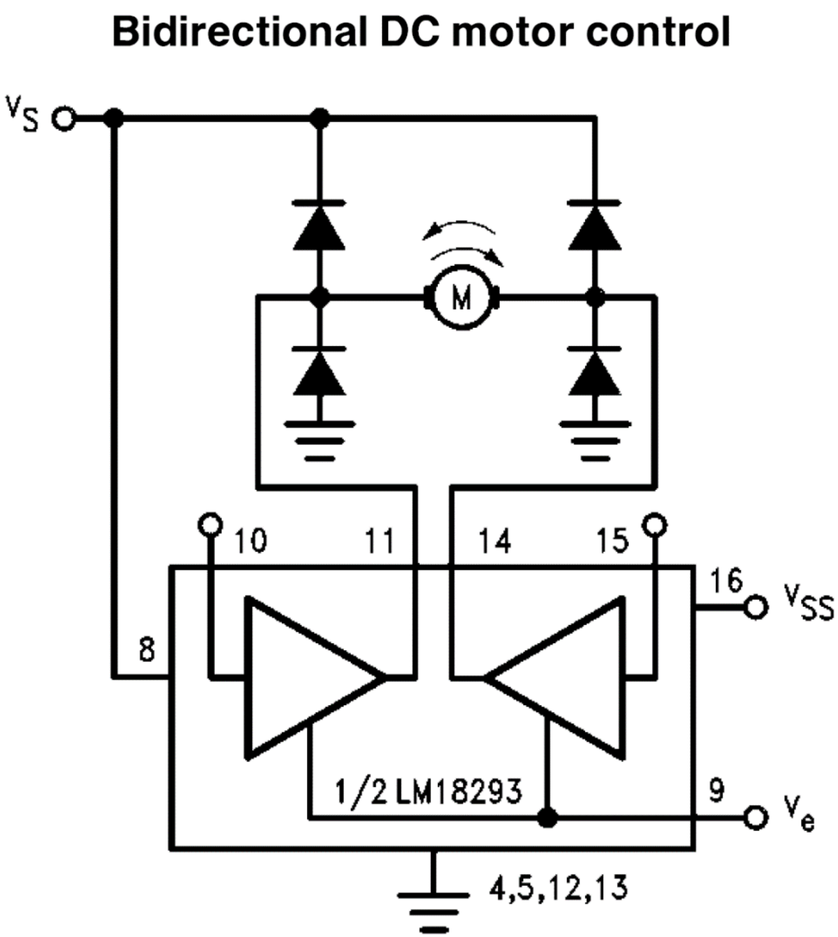
Enable 1 activates outputs 1 & 2

Enable 2 activates outputs 3 & 4

TL/H/8706-2

Output current : 1A per channel for L293 (600mA for L293D)

Bidirectional Connection

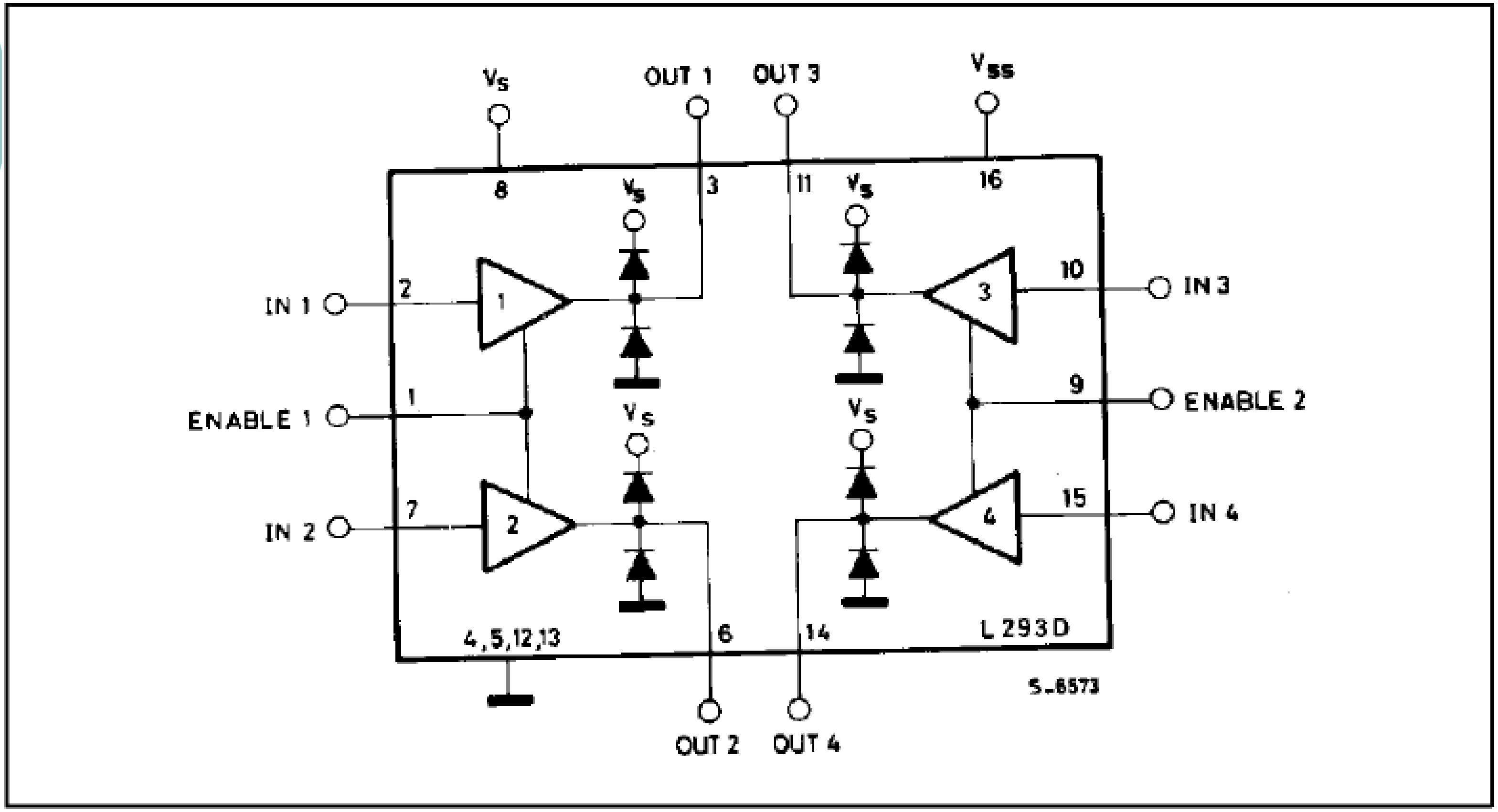


Pin input specifications

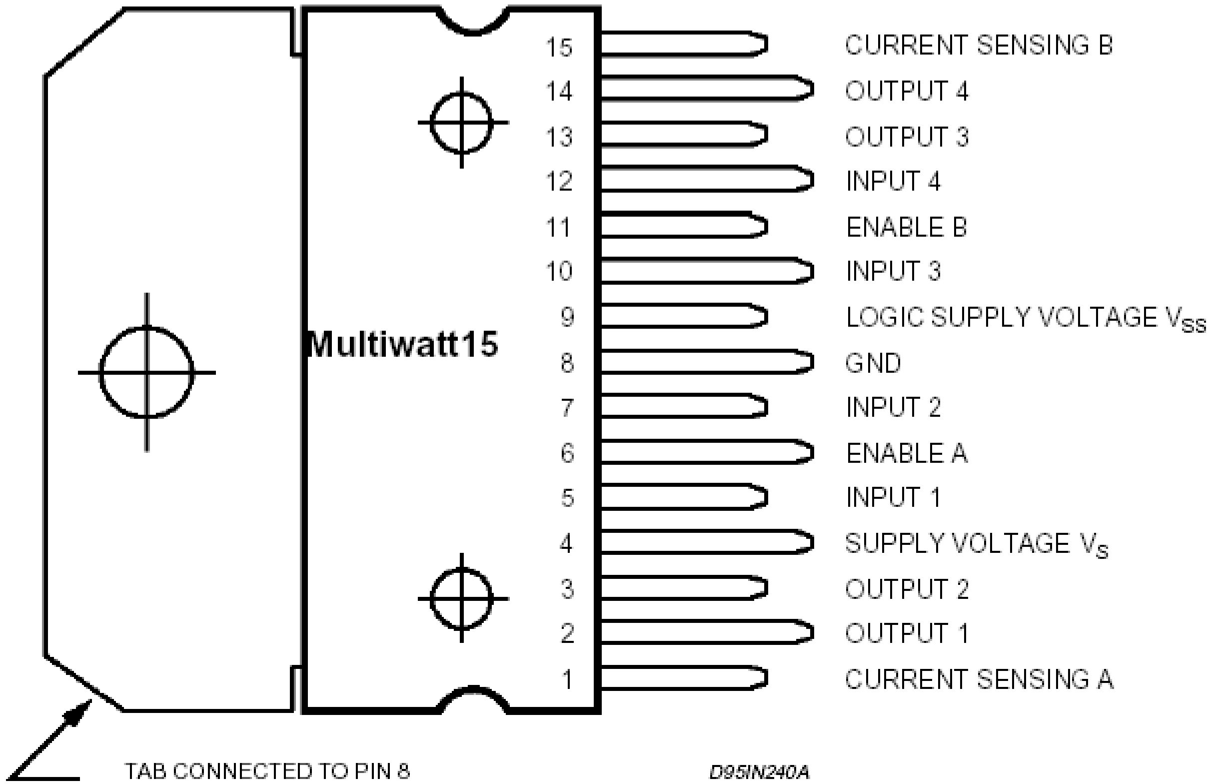
Inputs		Function
V_E = H	Pin 10 = H Pin 15 = L	Turn CW
	Pin 10 = L Pin 15 = H	Turn CCW
	Pin 10 = Pin 15	Fast Motor Stop
V_E = L	Pin 10 = X Pin 15 = X	Free Running Motor Stop

L = Low H = High X = Don't care

L293D Motor Driver with Diodes, 600mA

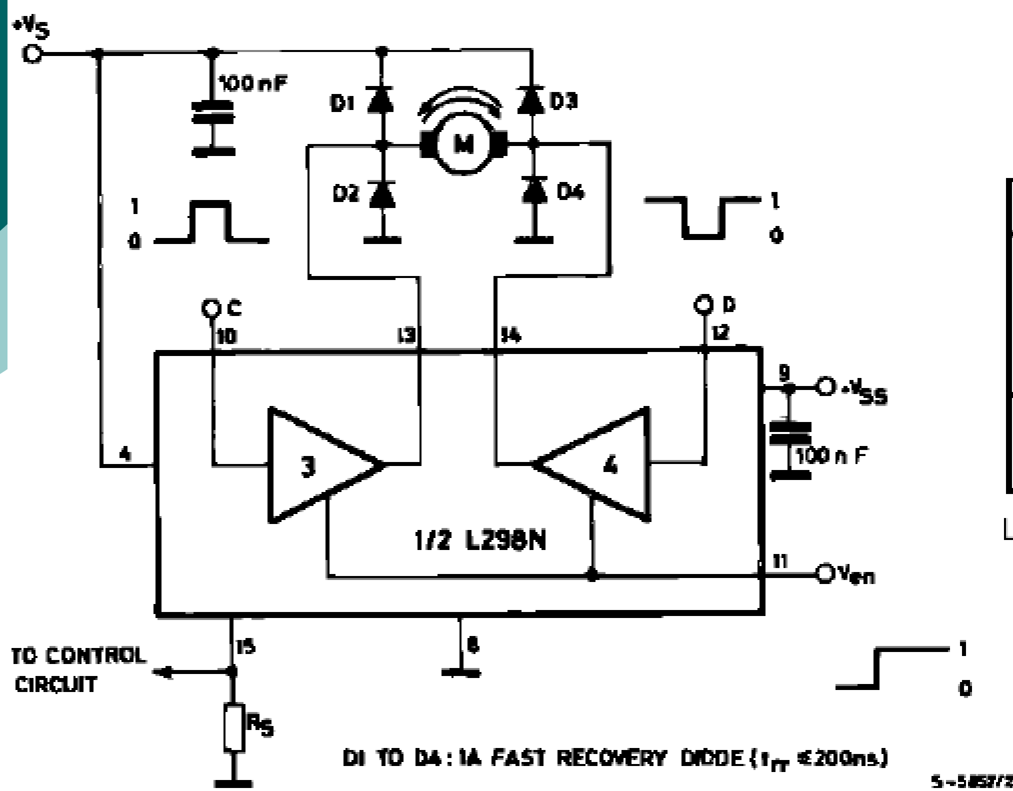


L298 Pin Assignment



Max. current : 2A for one side

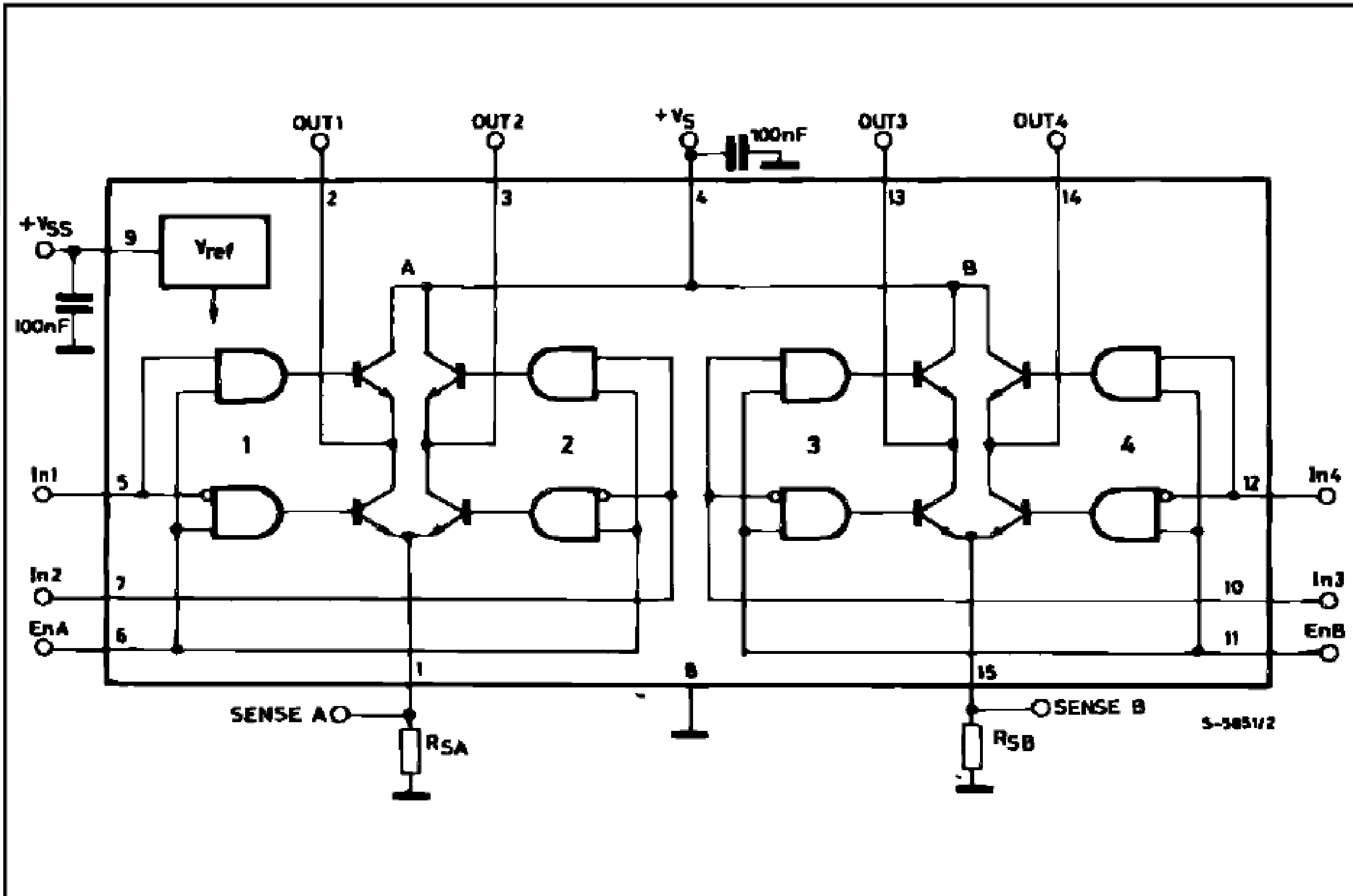
Bi-directional Motor Connection of L298



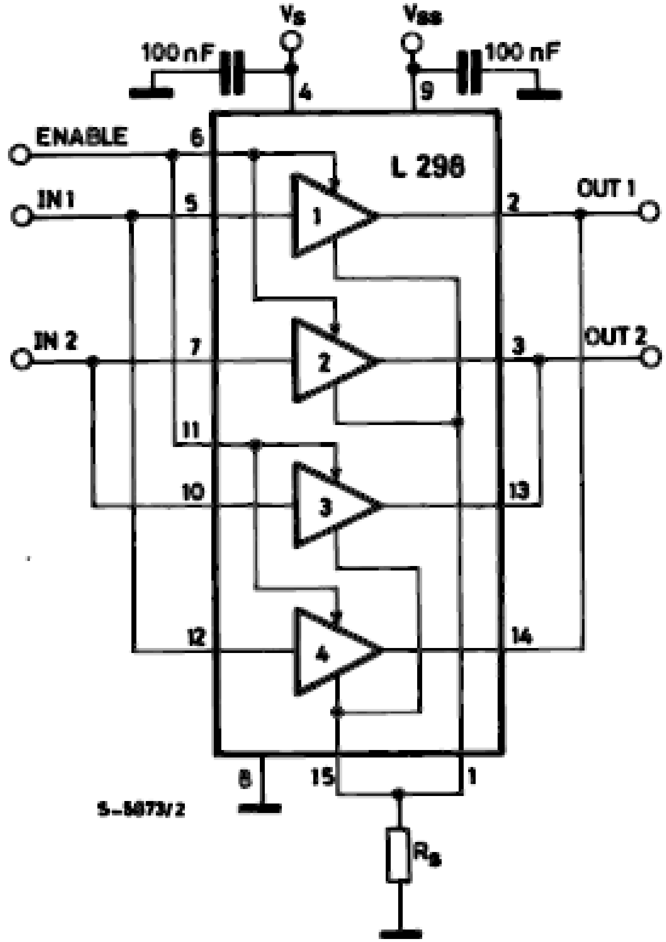
Inputs		Function
V_{en} = H	C = H ; D = L	Forward
	C = L ; D = H	Reverse
	C = D	Fast Motor Stop
V_{en} = L	C = X ; D = X	Free Running Motor Stop

L = Low H = High X = Don't care

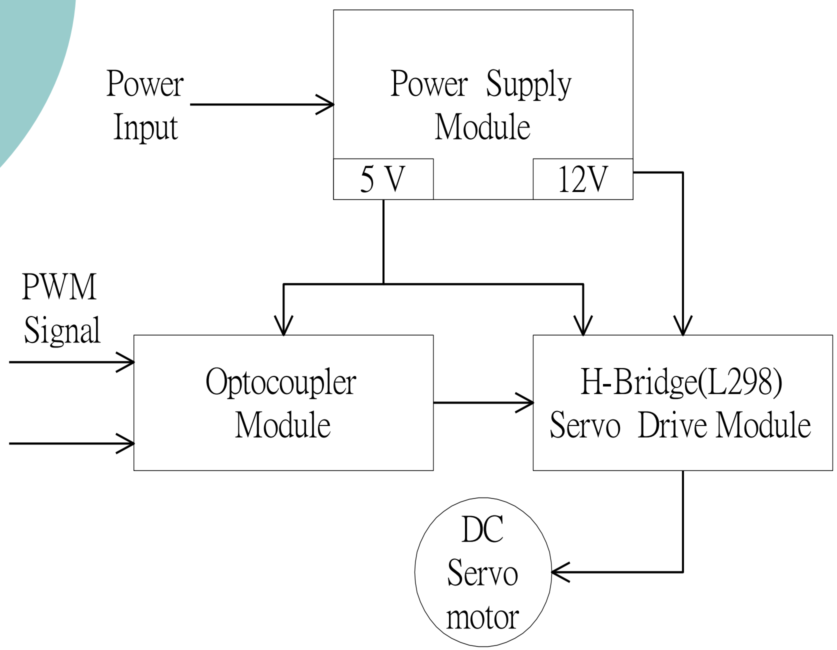
L298 Two-Channel H-Bridge Circuit, 2A

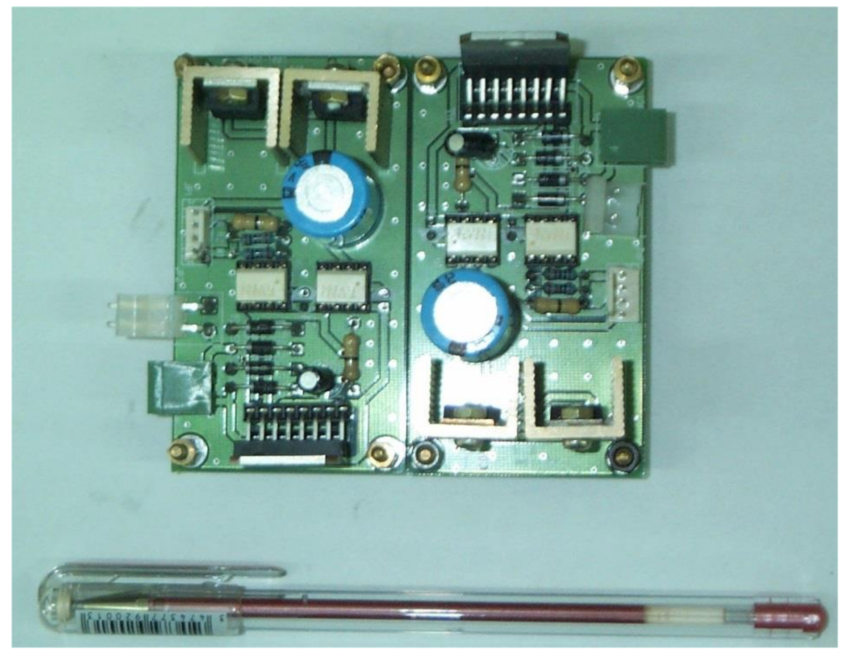


Parallel Configuration



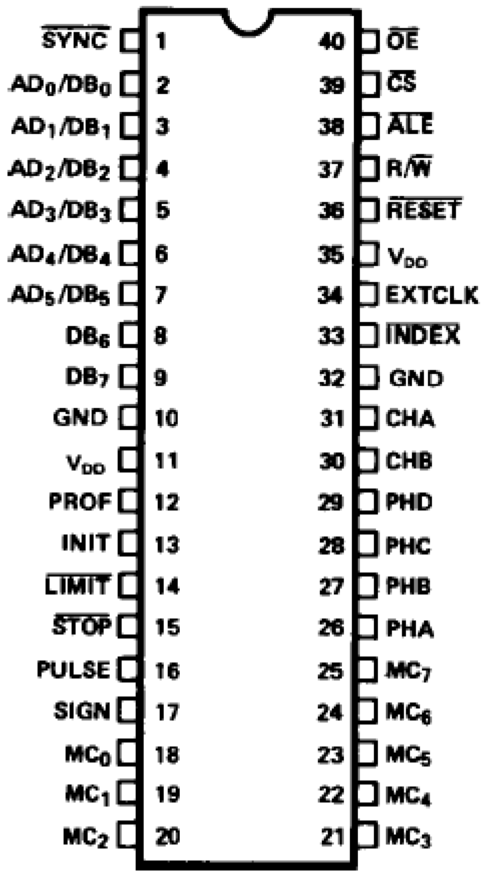
Servo Motor Driver Circuit

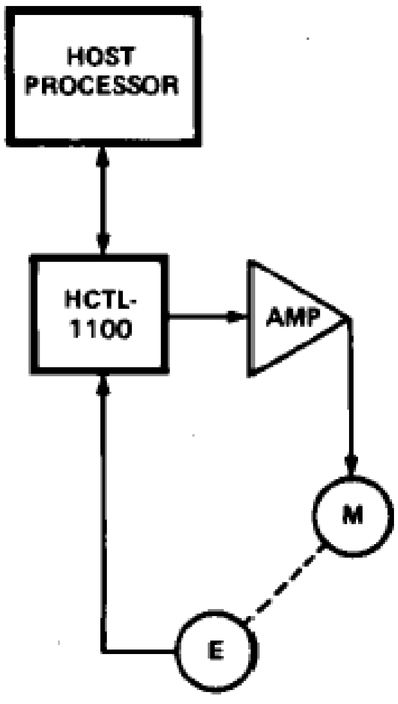




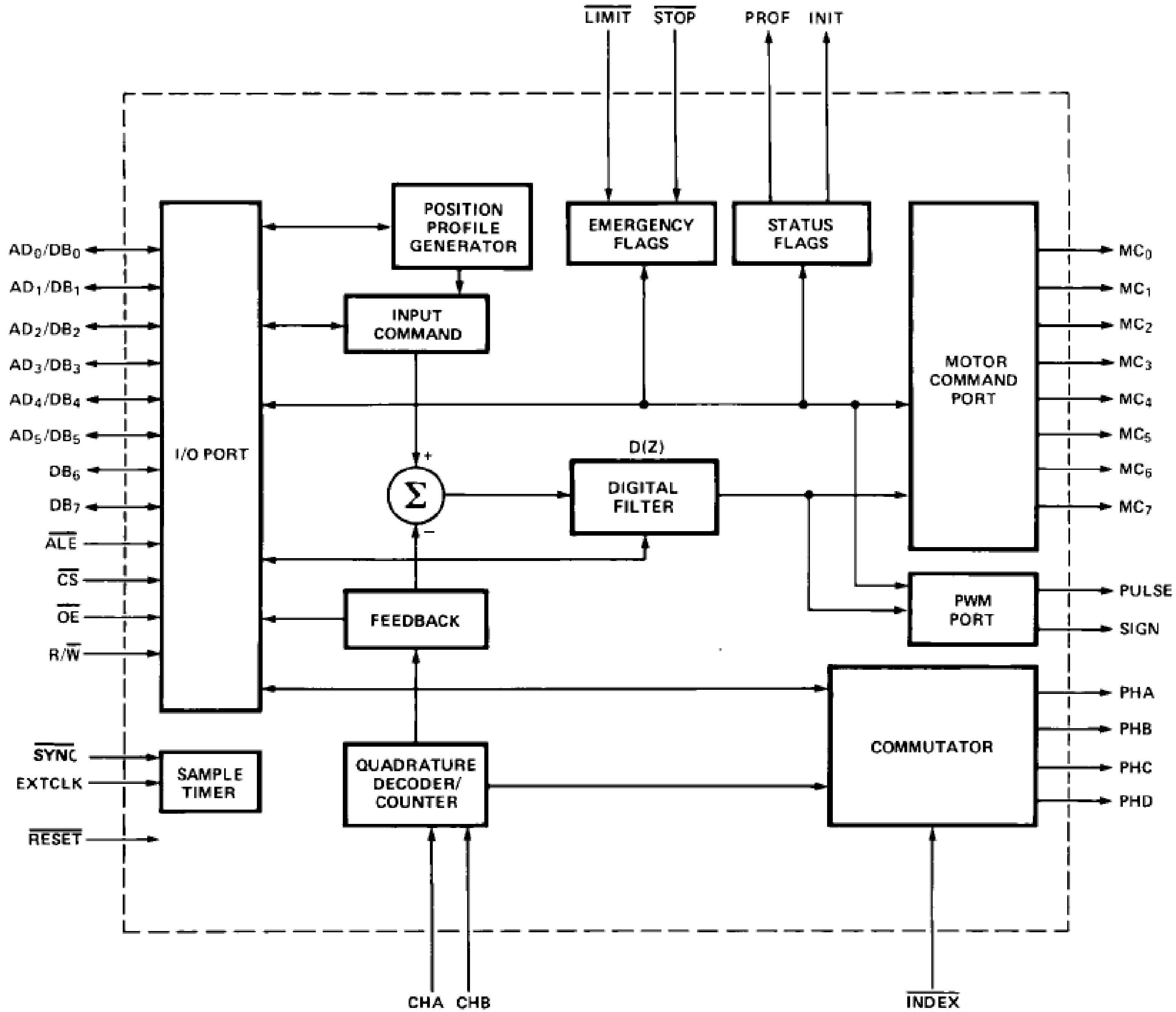
Motion Controllers

HCTL-1100 Pin Assignment

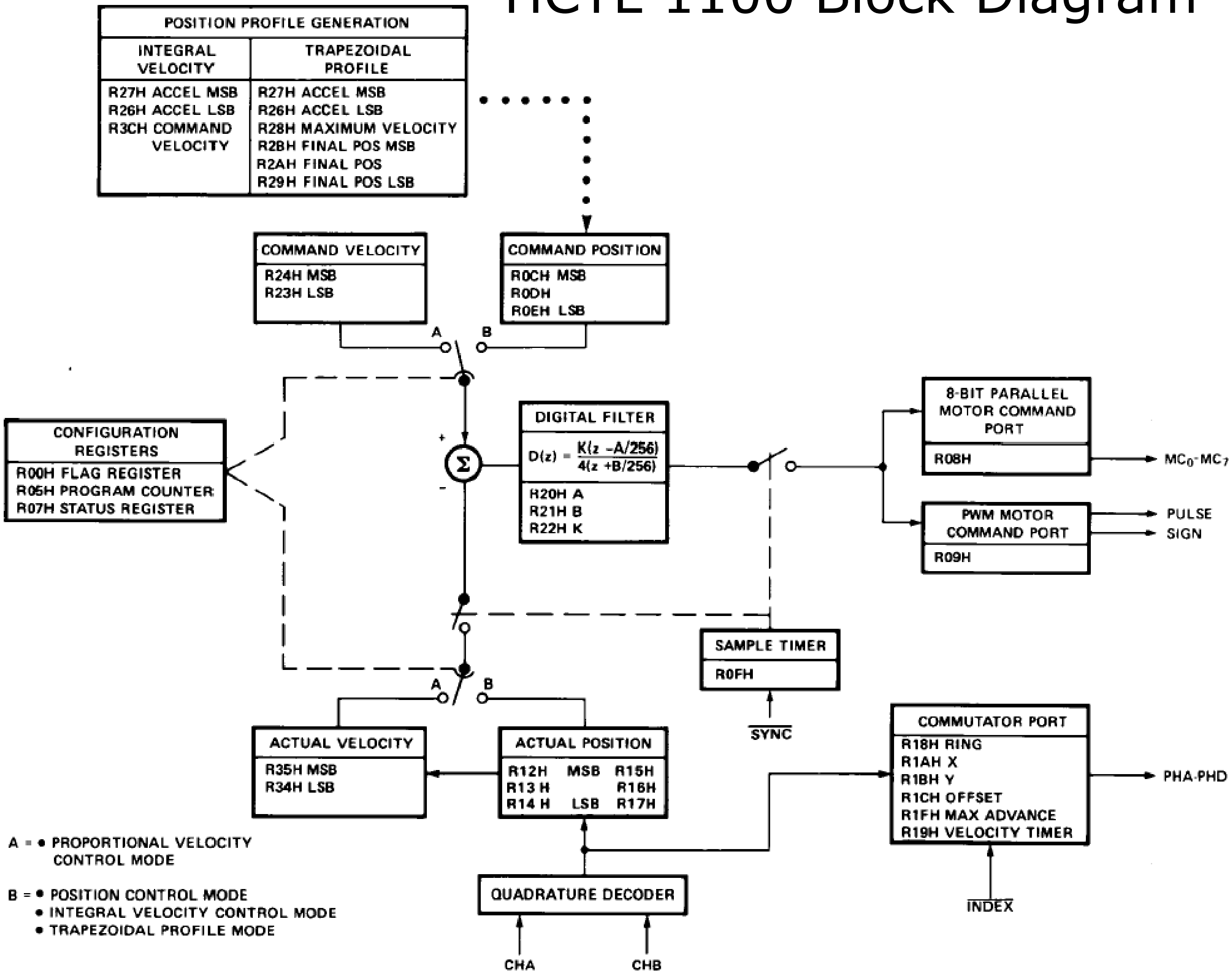




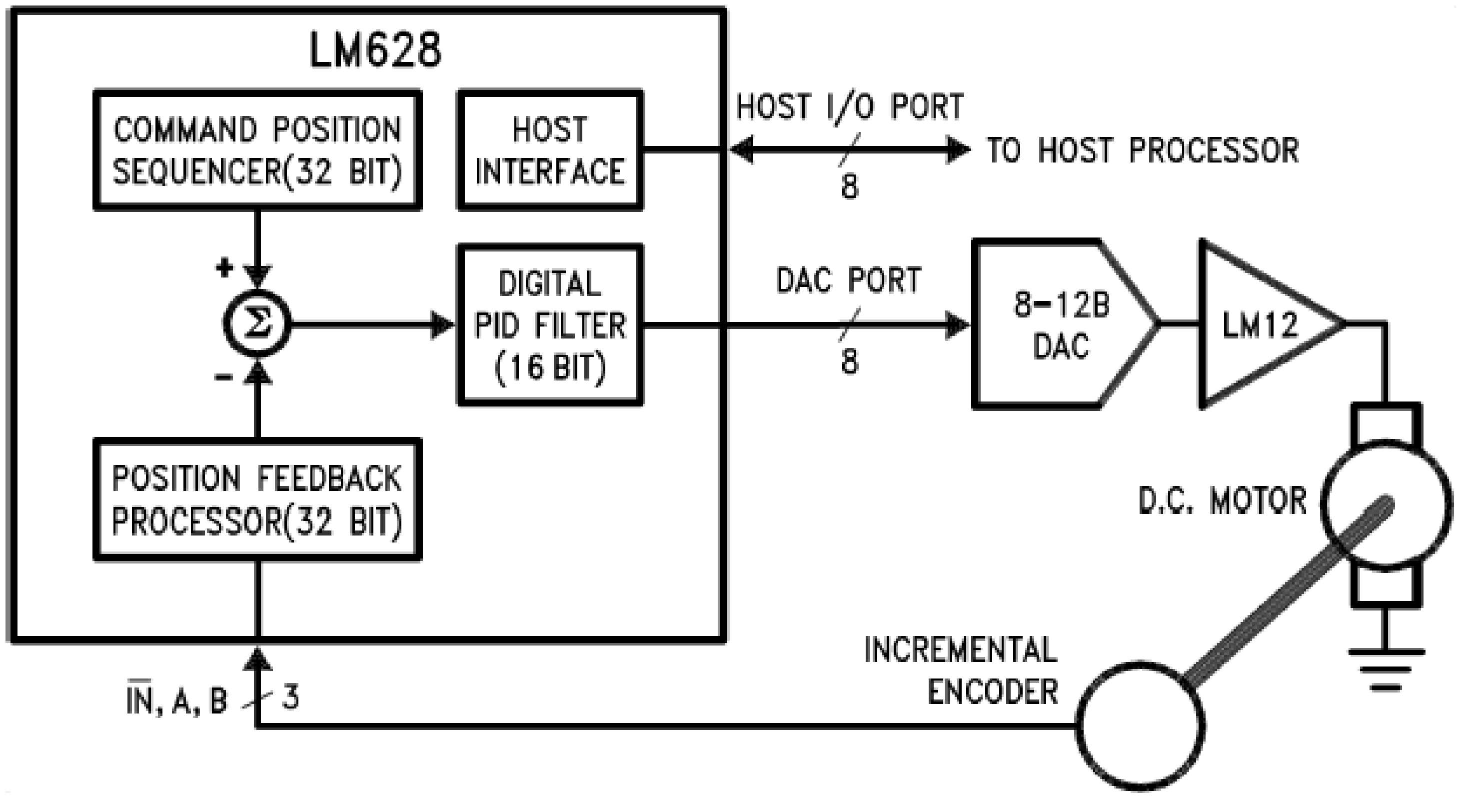
Internal Structure of HCTL-1100



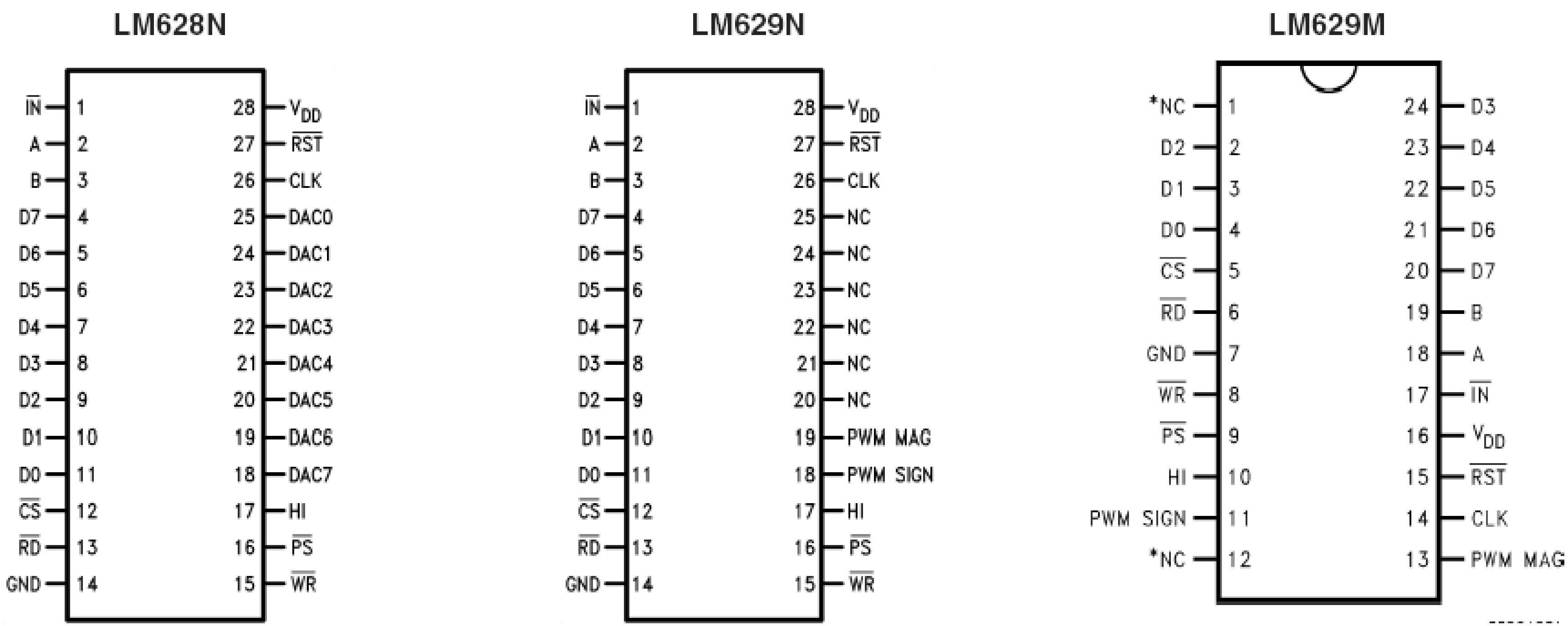
HCTL-1100 Block Diagram



LM628/LM629 Block Diagram



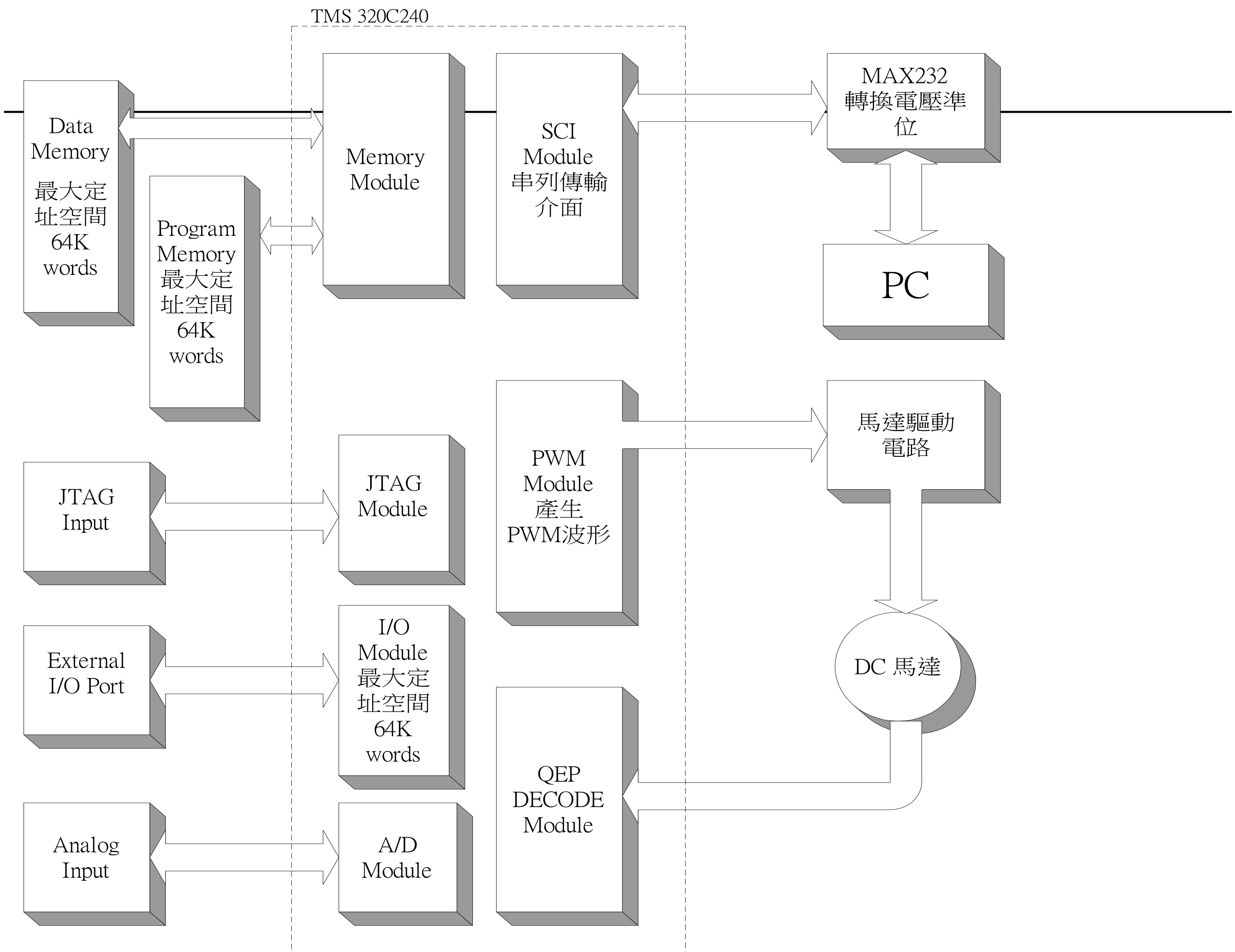
LM628/LM629 Pin Assignment



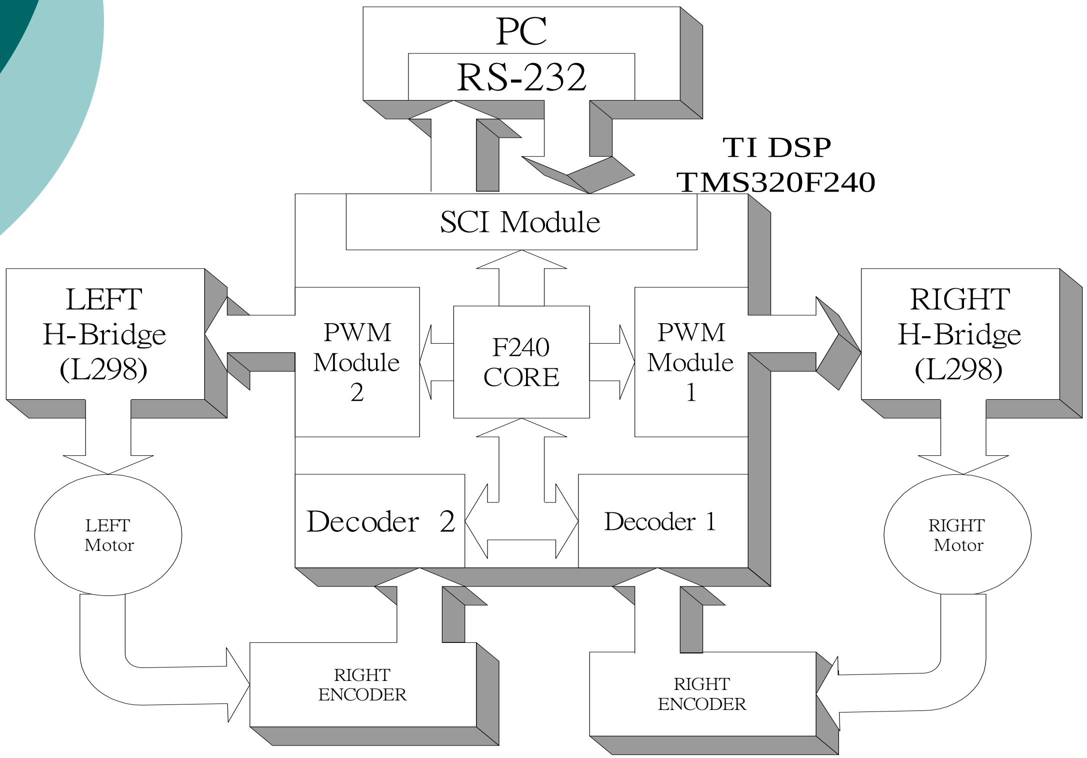
DSP Motion Control Card

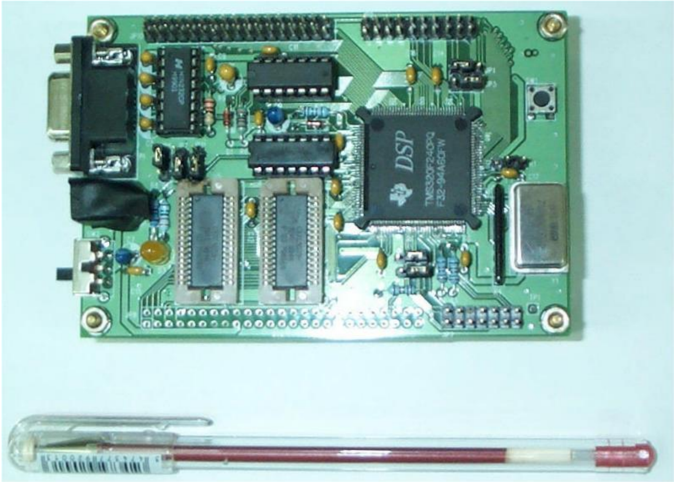
- Characteristics:
  - DSP TMS 320F240
  - 16 K Words Flash Program Memory
  - 32 K Words SDRAM Memory
  - PWM Signal module with 2 decoder circuits
  - RS-232 serial link
  - Photo-coupler isolator
  - A/D and I/O Port extention

System Block Diagram



DSP-Based Motion Control Card

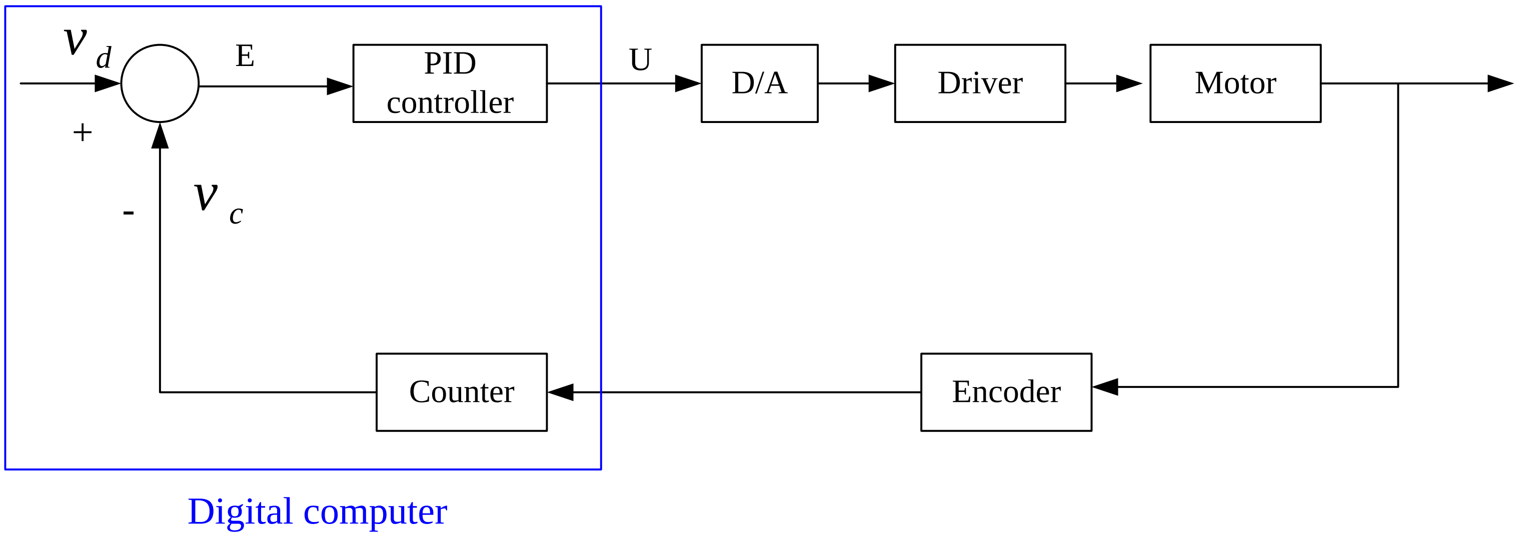




Motion Control Test (1/3): Motor Data

- DC Motors
  - GM9236S019 model number
  - Working voltage: 12 V
  - Gear ratio : 19.7 : 1
  - Max rotating speed: 4.1 轉/秒
  - Encoders : 500 PPR
  - Max Load : 500 N-m
  - Count=19.7*500*4*1.024m* w(revolution/s)

Digital PID Controller



$$\frac{U(z)}{E(z)} = H(z) = k_p + k_i \cdot \frac{Tz}{z-1} + k_d \frac{z-1}{Tz}$$

Discrete form of a PID controller

$$z(z-1)\frac{U(z)}{E(z)} = k_p z(z-1) + k_i T z^2 + \frac{k_d}{T}(z-1)^2$$

$$\text{multiplied by } \frac{1}{z^2}$$

$$(1-z^{-1})\frac{U(z)}{E(z)} = k_p(1-z^{-1}) + k_i^{'} + k_d^{'}(1-2z^{-1}-z^{-2})$$

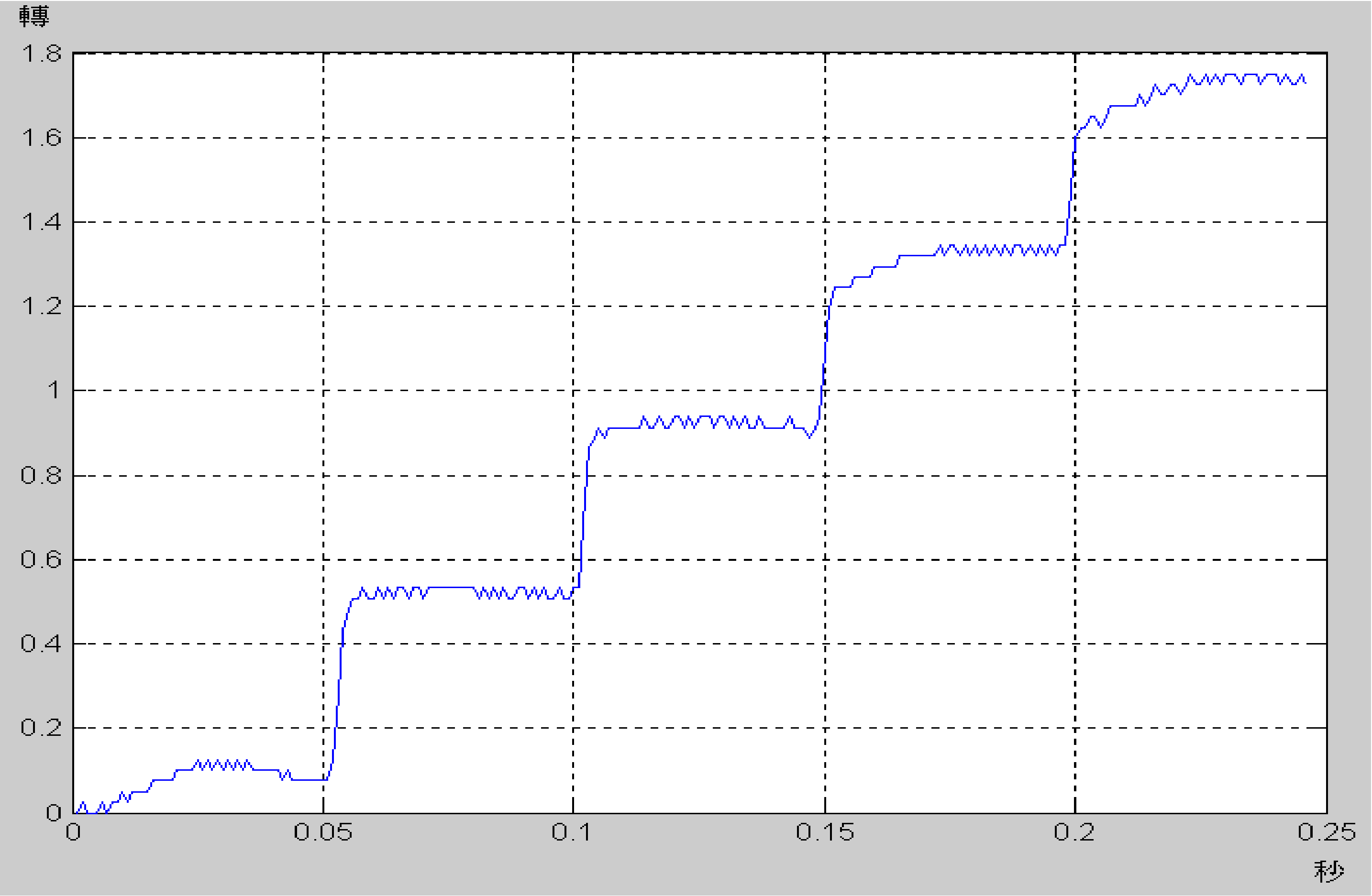
$$(1-z^{-1})U(z) = [k_p(1-z^{-1}) + k_i^{'} + k_d^{'}(1-2z^{-1}-z^{-2})]E(z)$$

$$u(k) = u(k-1) + k_p[e(k)-e(k-1)] + k_i^{'}e(k) + k_d^{'}[e(k)-2e(k-1)-e(k-2)]$$

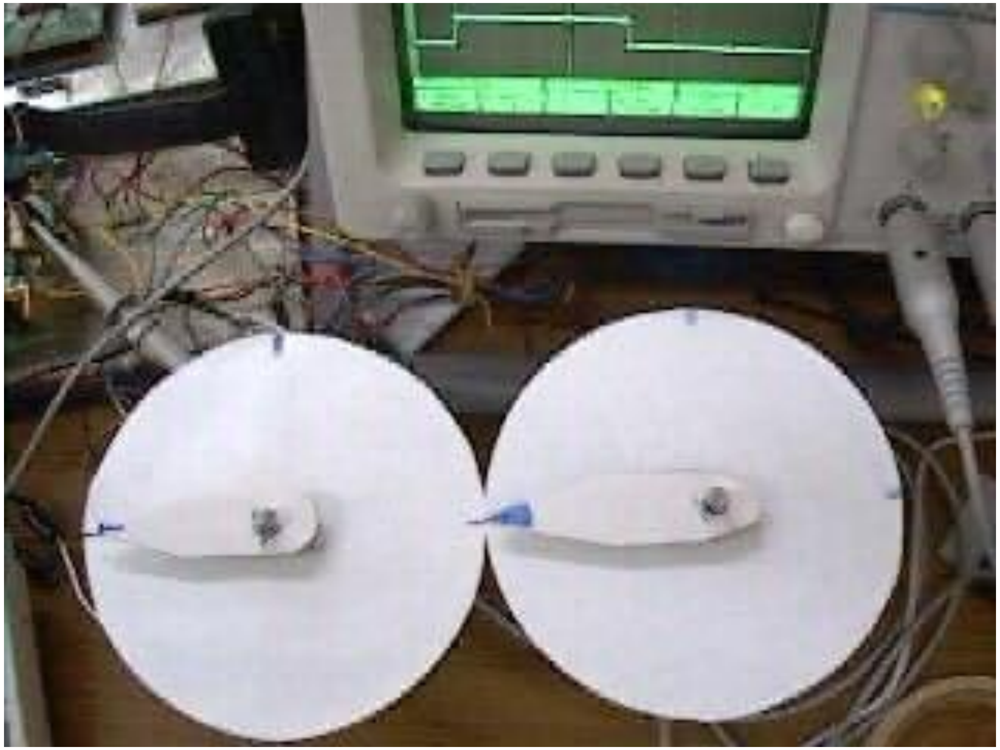
Motion Control Test (2/3) : Step Response

- Rise time
  - Time to achieve 20*0.9=18→ 5ms
- Max. over shoot
  - (0.53-0.5) / 0.5 = 0.06
- Settling time
  - Time to arrive at 5% range of steady-state value →7 ms

Motion Control Test (3/3): Tracking Performance



Video Clip of Two-Axis Motion Control



CP #2 Robot Motion Control

The purpose of this checkpoint is to make sure you can control the motion of DC motors by using PWM with Raspberry Pi and Arduino.

Task:

Construct the basic motion platform of the robot using the chassis.

Demonstrate your robot performing the following actions by giving PWM value to the motor individually.

- Move forward. (25%)
- Move backward. (25%)
- Turn right. (15%)
- Turn left. (15%)
- How straight when moving forward. (20%)