Electrical Actuation Systems

Textbook: W. Bolton, “Mechatronics --- Electronic control systems in mechanical and electrical engineering,” 5th edition, Pearson Education Limited 2012, Chap 9

Ref. book: J. Edward Carryer, R. Matthew Ohline, Thomas W. Kenny, “Introduction to Mechatronic Design,” Prentice Hall 2011

線上學習網站：https://www.electronics-tutorials.ws

PowerPoint 中部分圖片擷取和修改自教科書和網路圖片

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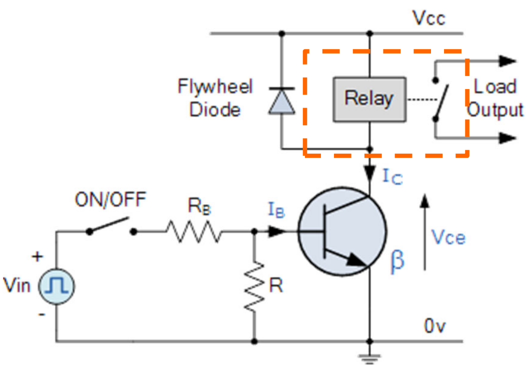
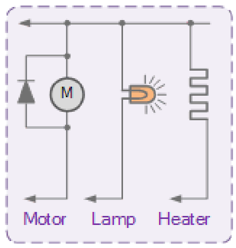
機械工程學系

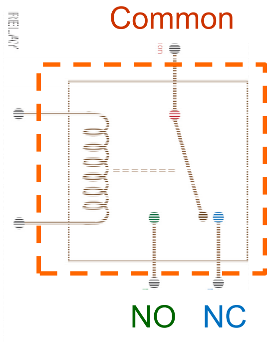
Solid-State Switches -1

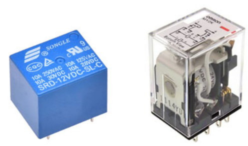
- Driving a relay using a NPN BJT





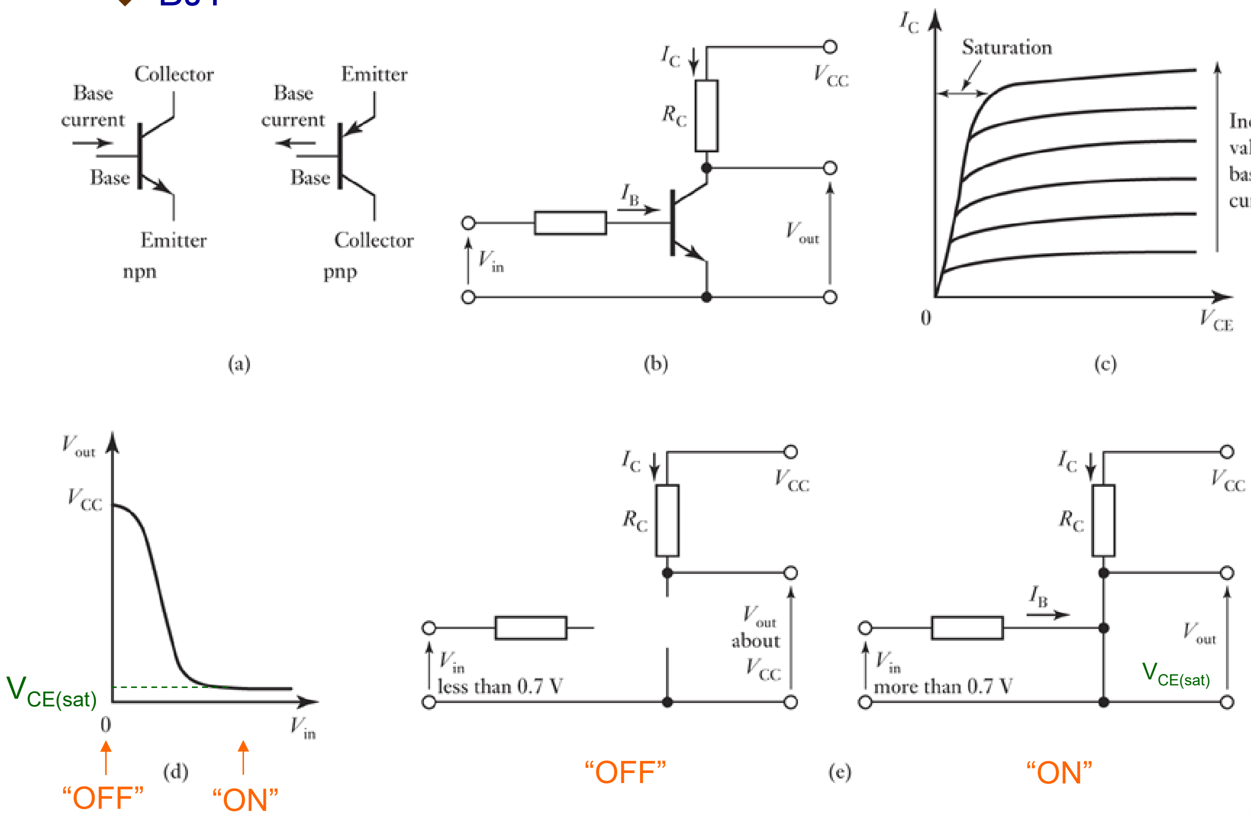
Different Collector Loads





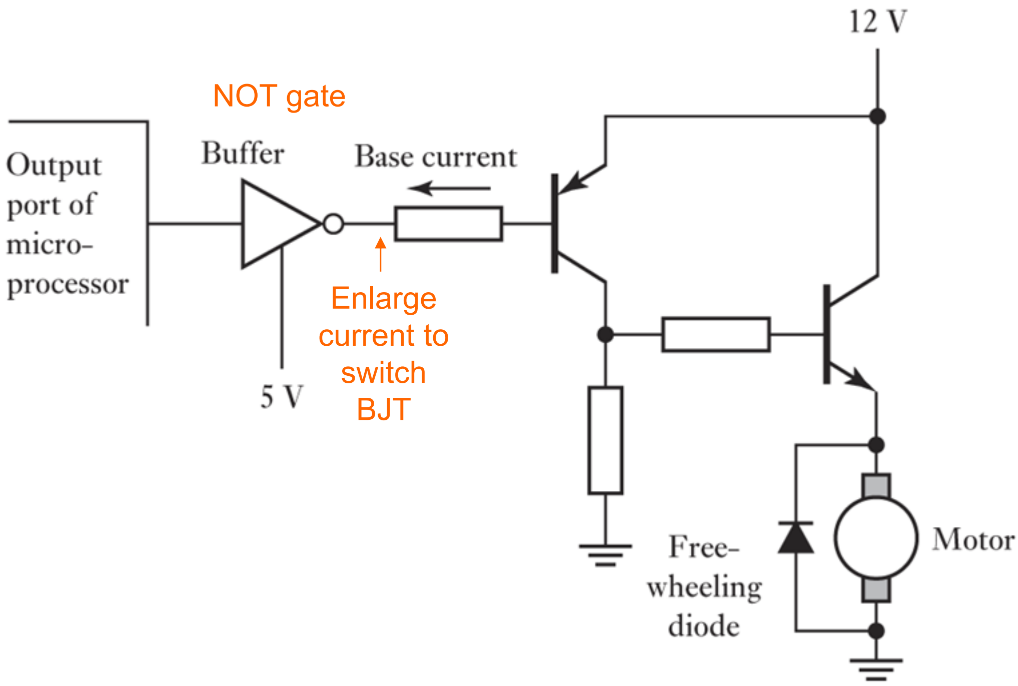
Solid-State Switches -2

- BJT



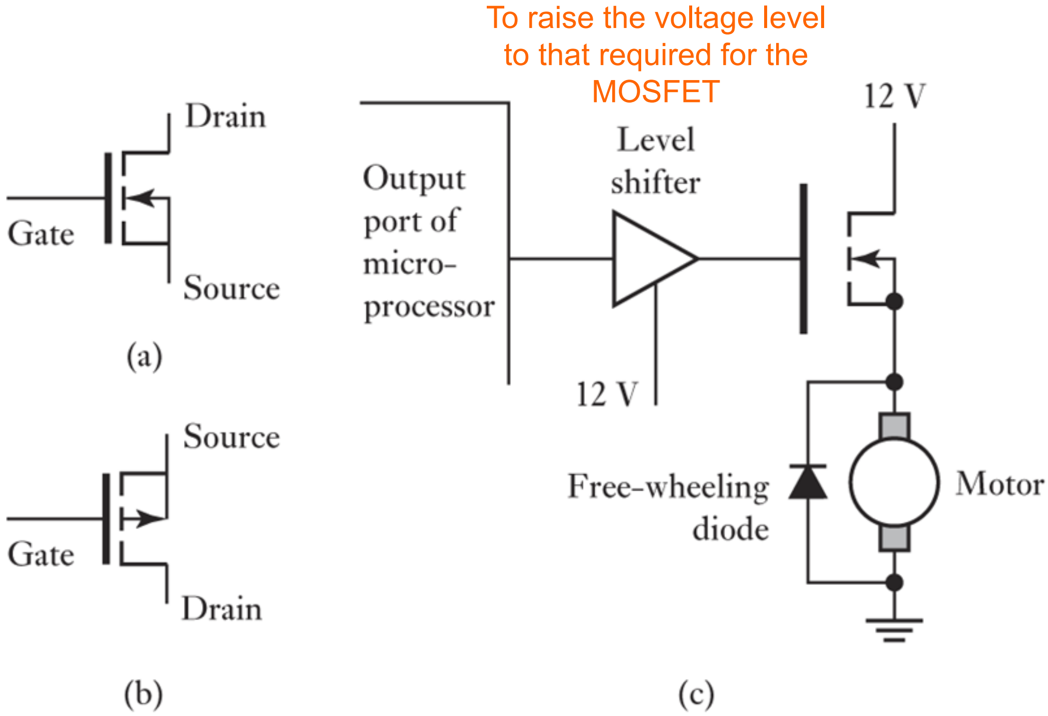
Solid-State Switches -3

- BJT



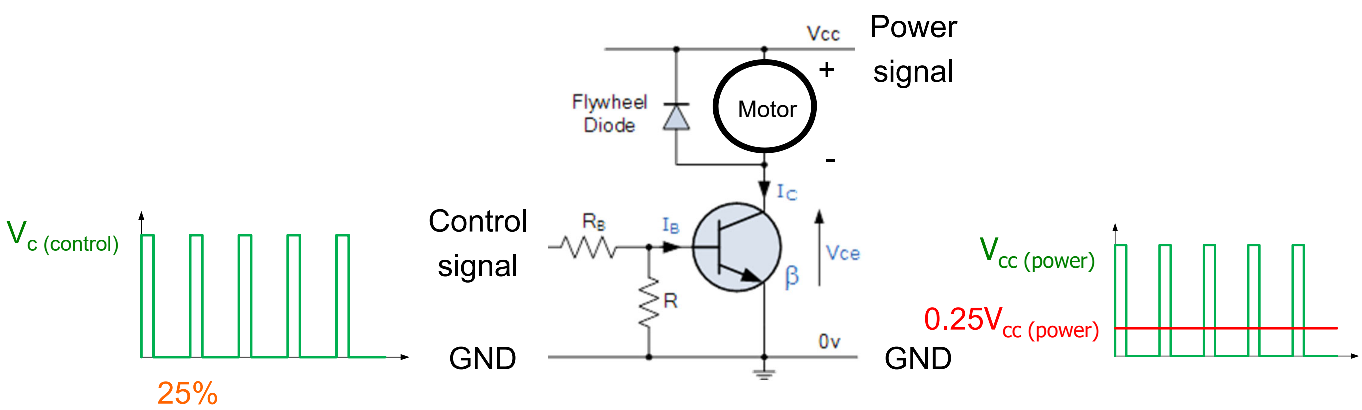
Solid-State Switches -4

- MOSFET



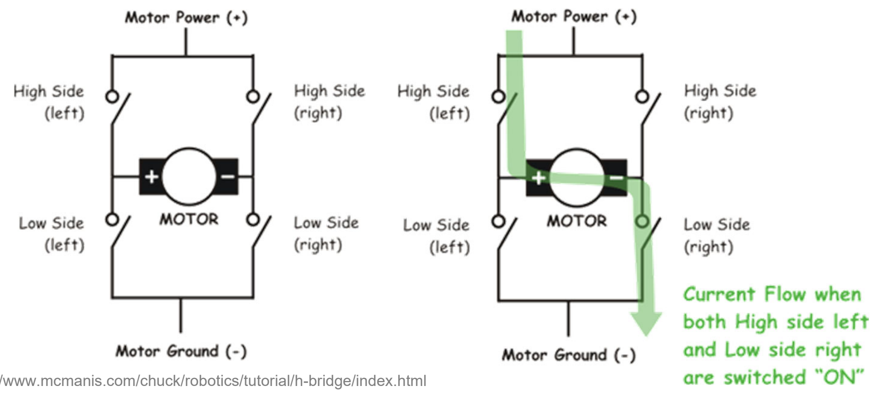
Motor Drive -1

- Using pulse-width-modulation (PWM) to modulate “equivalent” DC voltage between motor terminals



Motor Drive -2

- Using a H-bridge to switch the polarity of a voltage applied to a load

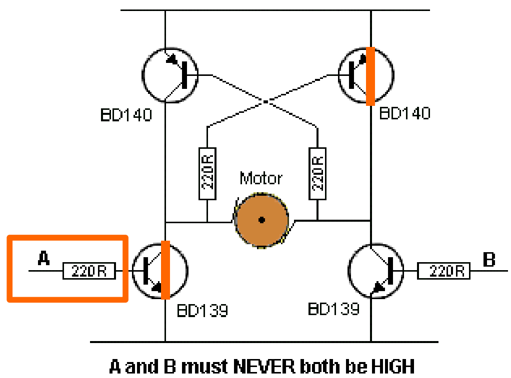


From: http://www.mcmanis.com/chuck/robotics/tutorial/h-bridge/index.html

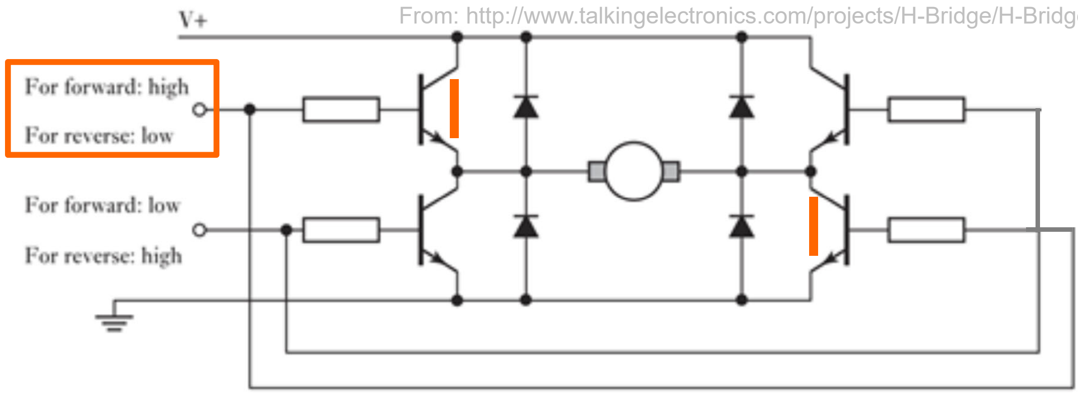
High side left	High side right	Low side left	Low side right	Motor motion
ON	OFF	OFF	ON	Clockwise rotation
OFF	ON	ON	OFF	Counterclockwise rotation
ON	ON	OFF	OFF	Brake
OFF	OFF	ON	ON	Brake
OFF	OFF	OFF	OFF	Free rotation

Motor Drive -3

- H bridge using four BJTs
  - One input controls two BJTs
    - PWM, control output voltage
  - Both inputs must NEVER be HIGH
  - THREE modes: forward, reverse, free fun

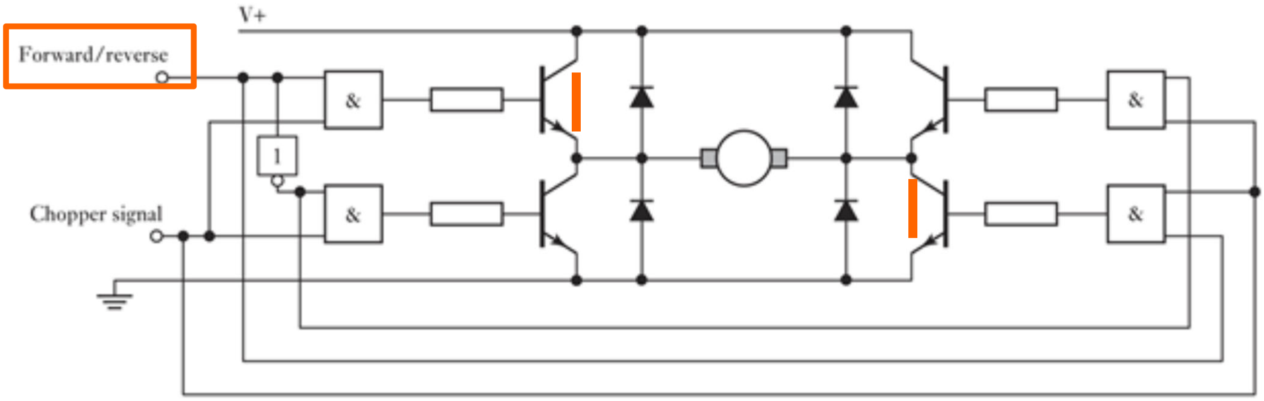


From: http://www.talkingelectronics.com/projects/H-Bridge/H-Bridge-1.html



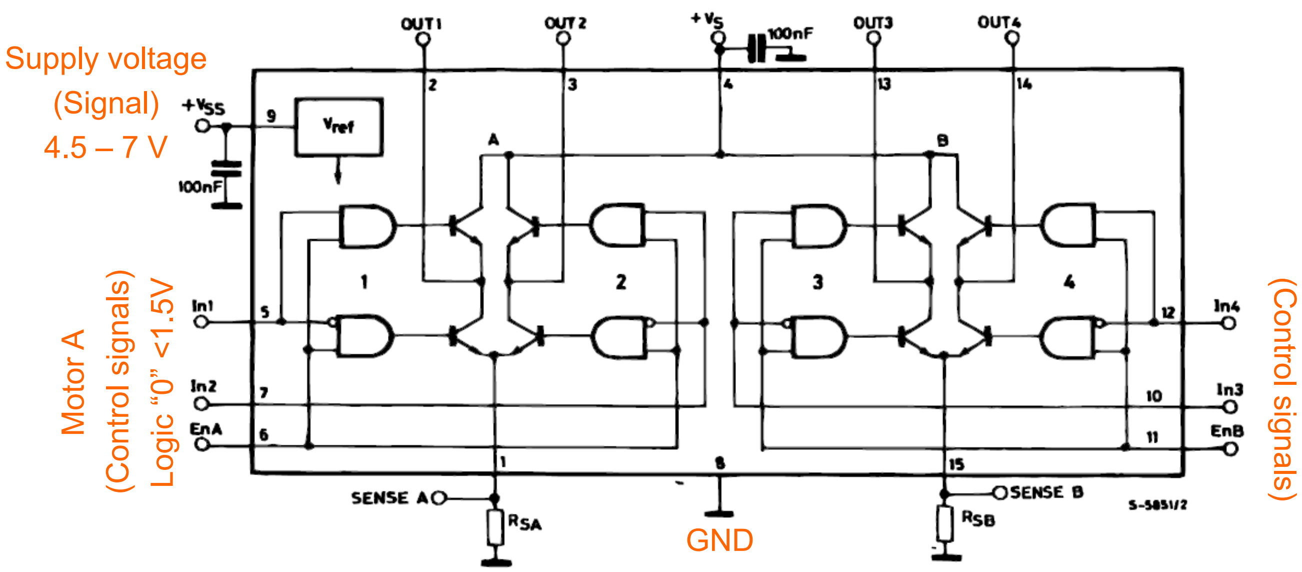
Motor Drive -4

- The H bridge using four BJTs
  - Using logic gates to transform control inputs to Forward/reverse (low-speed DIO) & Chopper signal (PWM, high speed DIO)
  - THREE modes: forward, reverse, free fun



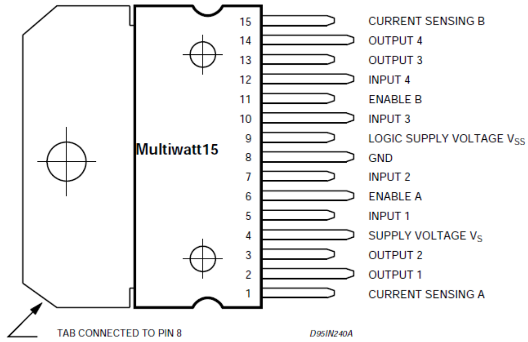
Motor Drive -5

- L298N full bridge driver
  - Block diagram

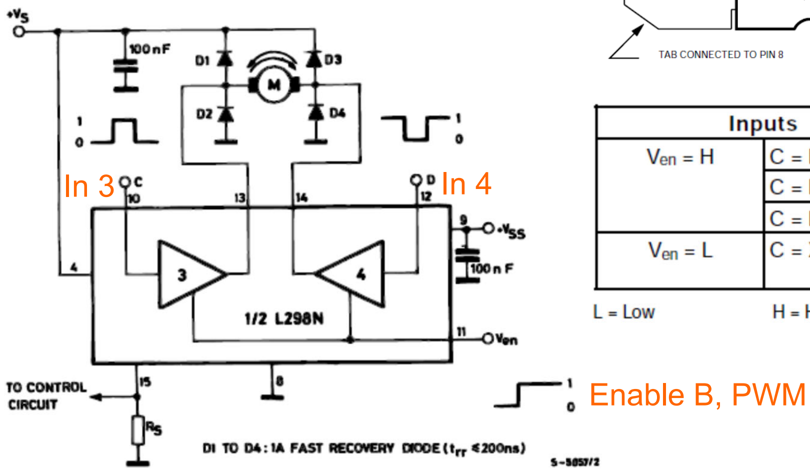


Motor Drive -6

- L298N full bridge driver
  - Pin connections



  - Bidirectional motor control

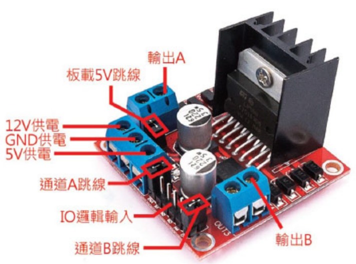


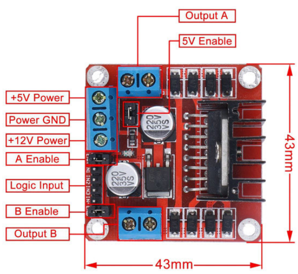
Inputs		Function
V_{en} = H	C = H ; D = L	Forward
	C = L ; D = H	Reverse
	C = D	Fast Motor Stop
V_{en} = L	C = X ; D = X	Free Running Motor Stop

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

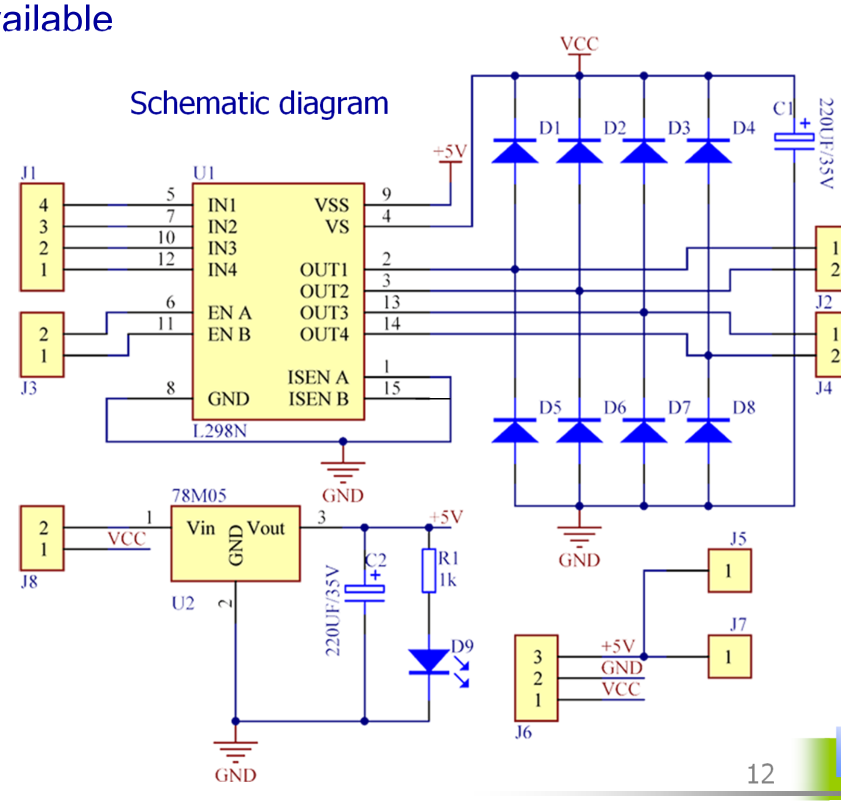
Motor Drive -7

- L298N full bridge driver
  - Many modules available





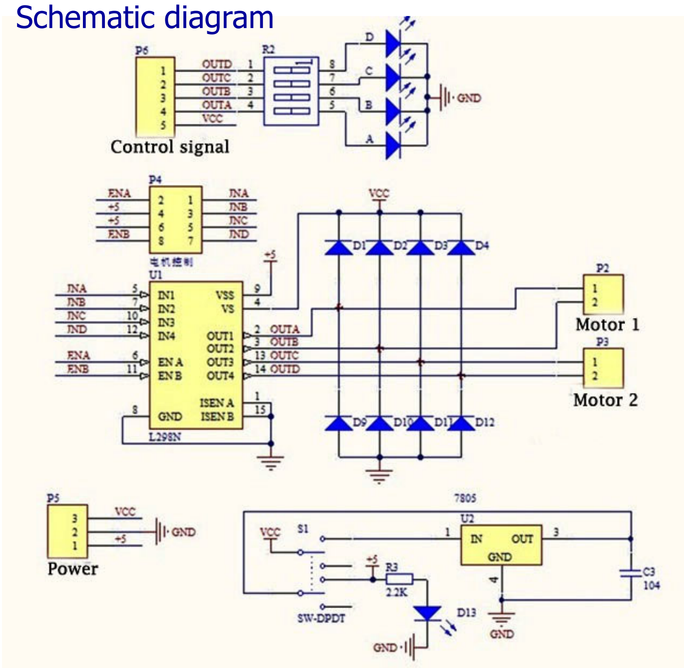
Schematic diagram

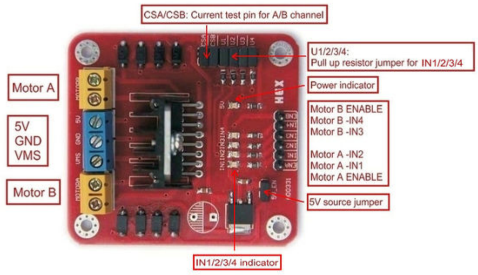


Motor Drive -8

- L298N full bridge driver
  - Many modules available

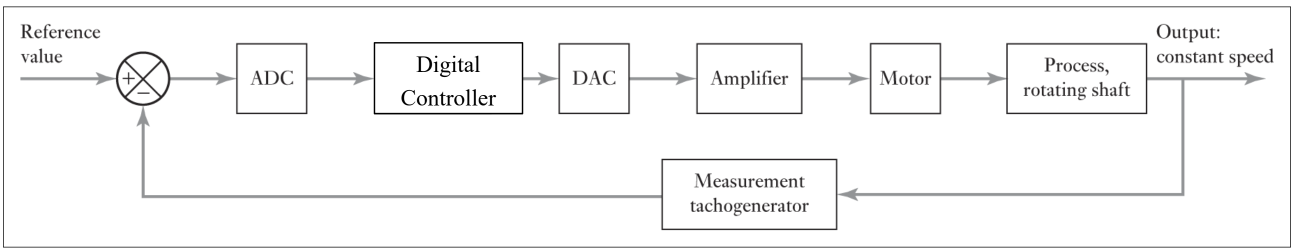
Schematic diagram





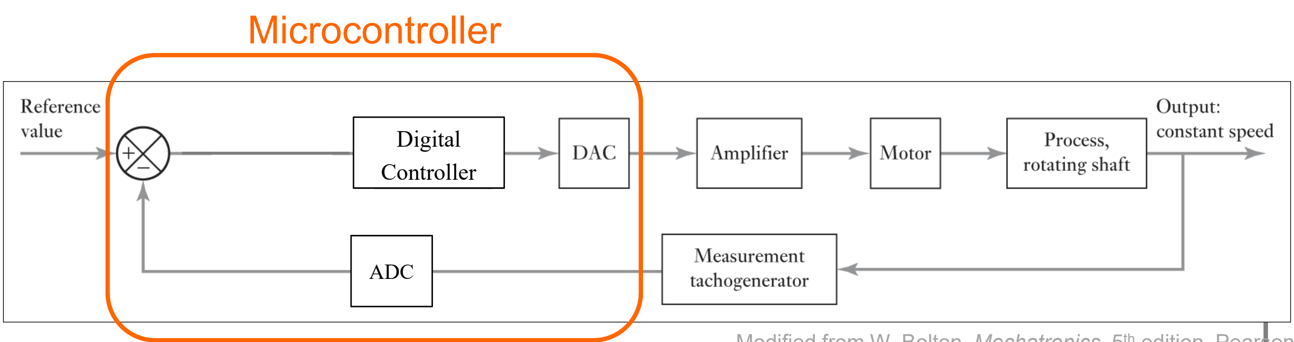
Motor Drive -9

- Ex: Revisit shaft speed control (Chap 1)
  - Using digital controller



From W. Bolton, *Mechatronics*, 5th edition, Pearson

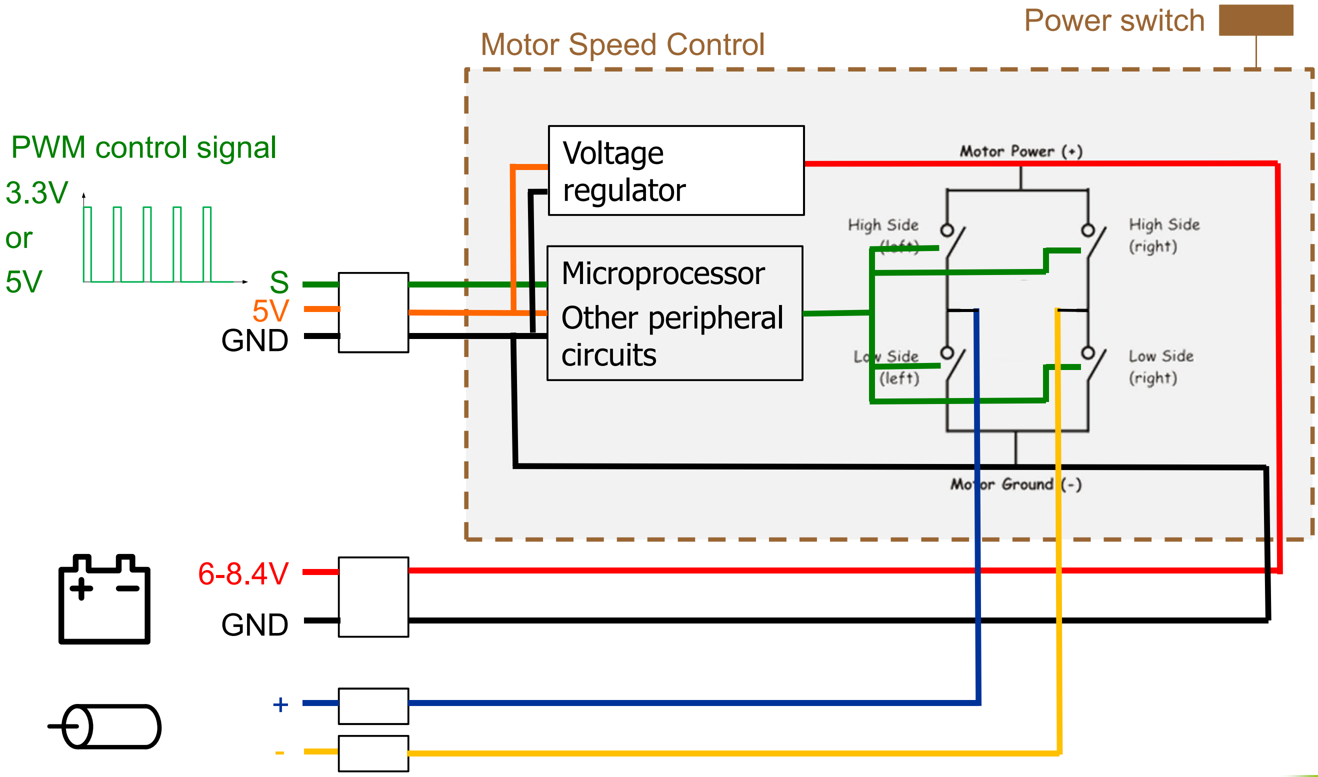
  - Using microcontroller



Modified from W. Bolton, *Mechatronics*, 5th edition, Pearson

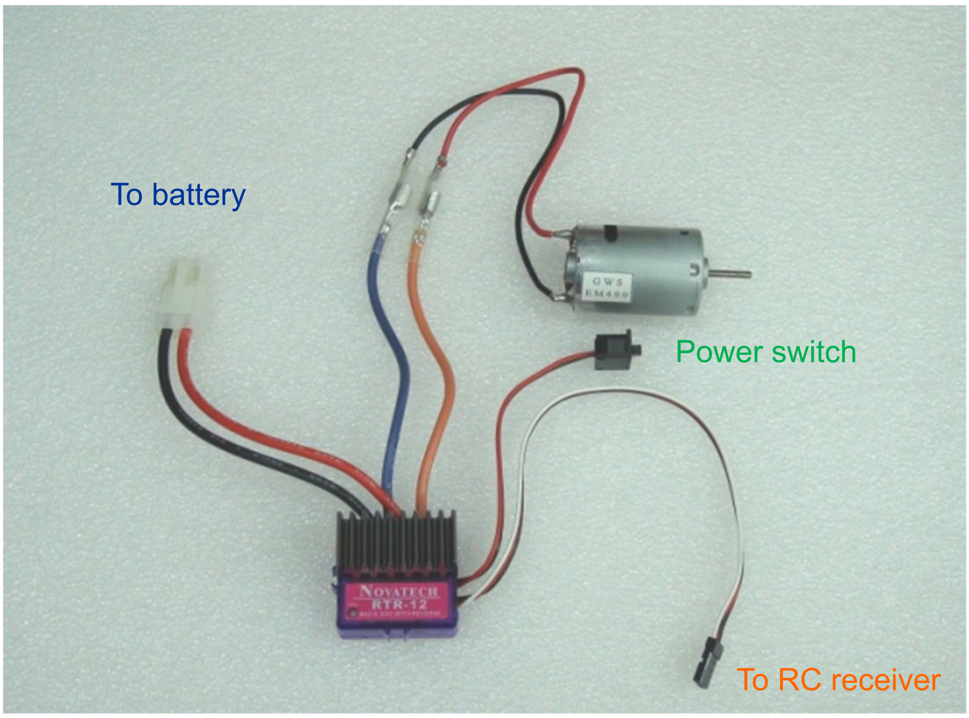
Motor Drive -10

- Electric speed controller (ESC) for RC vehicles



Motor Drive -11

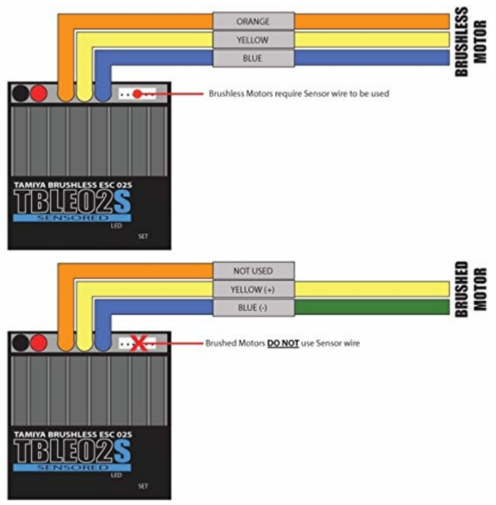
- Electric speed controller (ESC) for RC vehicles



Motor Drive -11

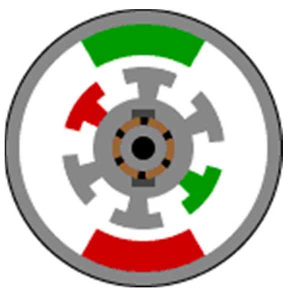
- Brushed
  - Two power wires
- Brushless
  - Three power wires
- Brushless sensored
  - Three power wires
  - Six sensor wires

Tamiya TBLE-02S



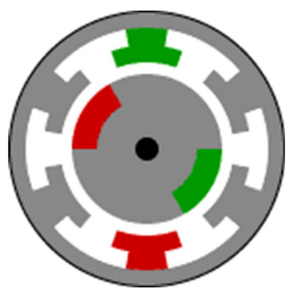
DC Motors

- Brushed DC motor



- The stator: The stationary outside part of a motor, permanent magnets
- The rotor: The inner part which rotates, windings
- Just as the rotor reaches alignment, the brushes move across the commutator contacts and energize the next winding

Brushless DC motor



- The rotor: permanent magnets
- The stator: windings
- The control electronics replace the function of the commutator and energize the proper winding

Brushed DC Motor -1

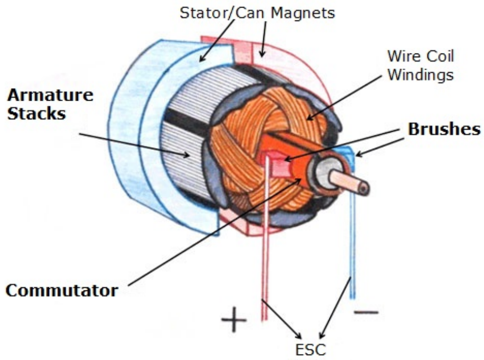
- Motors for RC vehicles

Standard 540

GWS EM400

TAMIYA RS-540 Type-RZ

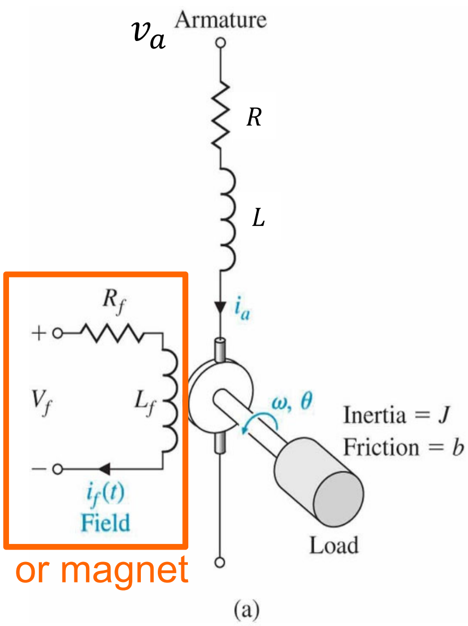
TAMIYA RS-540 Type-BZ

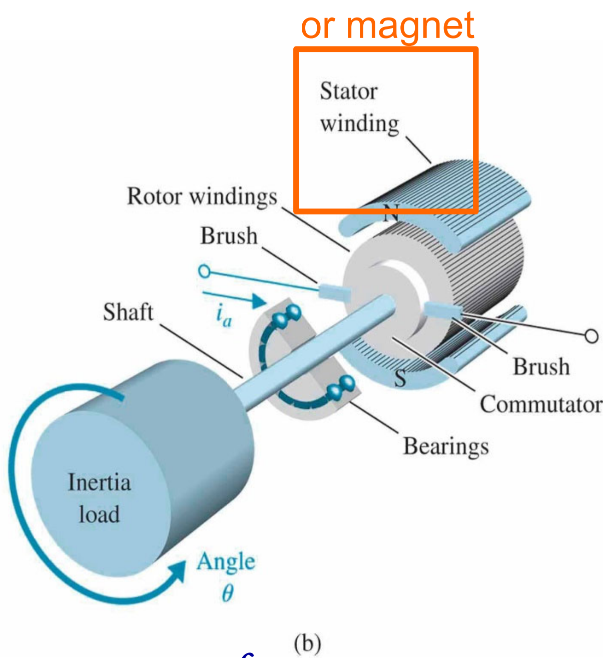


資料來源： http://www.brushlessrcmotor.com/brushed-rc-motor-information/

Brushed DC Motor -2

- DC motor diagram





$$\tau = k_1 \emptyset i_a = k_1 k_f i_f i_a = (k_1 k_f i_f) i_a = k_m i_a \xrightarrow{\mathcal{L}} T(s) = k_m I(s)$$

Air-gap flux

Armature-controlled

Motor constant (torque constant)

Brushed DC Motor -3

- Modeling

Mechanical

$$\tau = J\ddot{\theta} + b\dot{\theta}$$
$$= J\dot{\omega} + b\omega$$

$\downarrow \mathcal{L}$

$$T = J\Theta s^2 + b\Theta s$$
$$T(s) = JW(s)s + bW(s)$$

Electrical

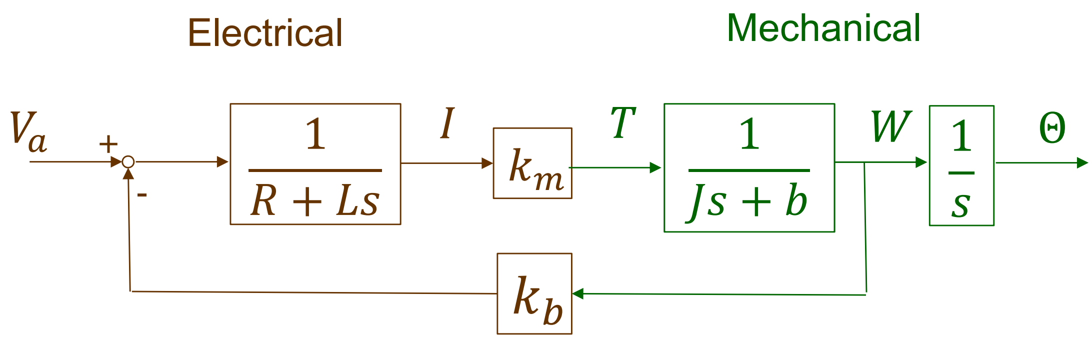
$$v_a = Ri + L\frac{di}{dt} + \underbrace{k_b\omega}_{\text{Back emf}}$$

$\downarrow \mathcal{L}$

$$V_a = RI + LIs + k_bW$$
$$I(s) = \frac{V_a(s) - k_bW(s)}{R + Ls}$$

$$JW(s)s + bW(s) = T(s) = k_mI(s) = k_m\frac{V_a(s) - k_bW(s)}{R + Ls}$$

Brushed DC Motor -4



$$G = \frac{\Theta}{V_a} = \frac{\Theta}{W}\frac{W}{V_a} = \frac{1}{s}\frac{k_m}{(R + Ls)(Js + b) + k_bk_m}$$

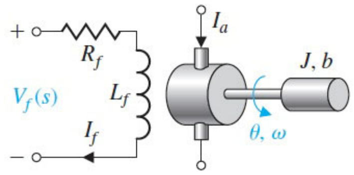
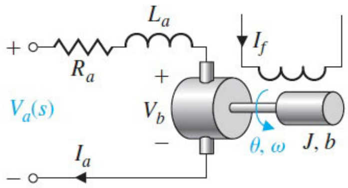
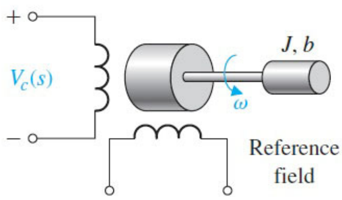
power: mechanical electrical

$$\tau \cdot \omega = (k_m i)\omega = (k_b\omega)i$$

$$k_m = k_b \quad unit: \left(\frac{N - m}{A}\right) \quad \left(\frac{V}{rad \cdot s}\right)$$

Brushed DC Motor -5

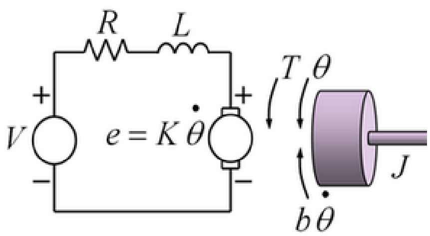
Table 2.5 *Continued*

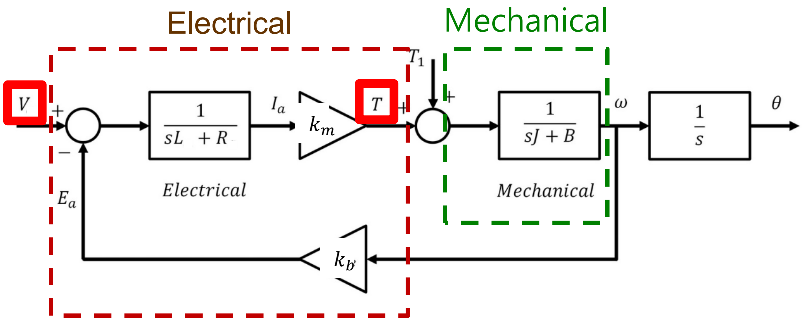
Element or System	G(s)
5. DC motor, field-controlled, rotational actuator 	$\dfrac{\theta(s)}{V_f(s)} = \dfrac{K_m}{s(Js+b)(L_f s+R_f)}$
6. DC motor, armature-controlled, rotational actuator 	$\dfrac{\theta(s)}{V_a(s)} = \dfrac{K_m}{s[(R_a+L_a s)(Js+b)+K_b K_m]}$
7. AC motor, two-phase control field, rotational actuator 	$\dfrac{\theta(s)}{V_c(s)} = \dfrac{K_m}{s(\tau s+1)}$, $\tau = J/(b-m)$, m = slope of linearized torque-speed curve (normally negative)

$$\tau = k_1 k_f i_f i_a = (k_1 k_f i_a) i_f = k_m i_f\,,\qquad I_f(s) = \frac{V_f(s)}{R_f + L_f s}$$

Brushed DC Motor -6

- Motor model





- Transfer function
  - *Voltage* to *Torque, s-domain*

$$T(s) = \frac{K_m(V(s) - K_b W(s))}{R + Ls}$$

Brushed DC Motor -7

- Assumption: steady-state or ideal inductance (*L=0*)

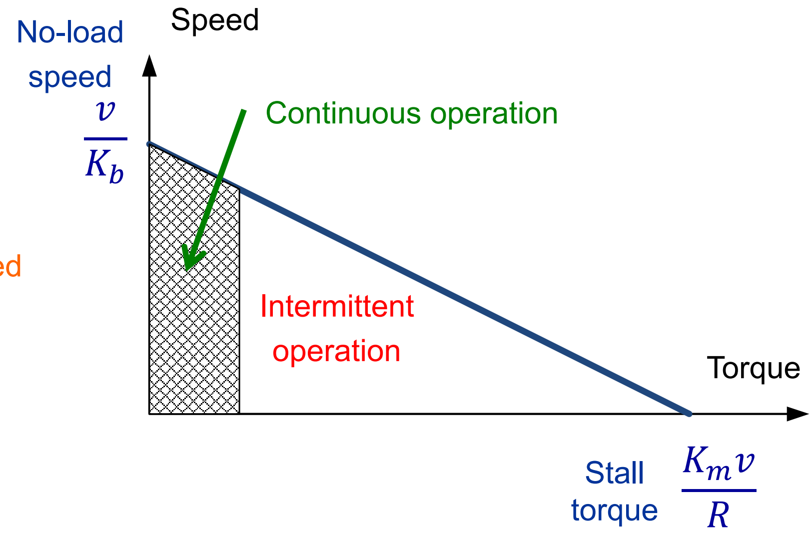
$$T(s) = \frac{K_m}{R} V(s) - \frac{K_m K_b}{R} W(s)$$

$\mathcal{L}^{-1}$ ⇩

$$\tau = \frac{K_m}{R} v - \frac{K_m K_b}{R} w$$

Torque | Voltage | Speed

Affine function



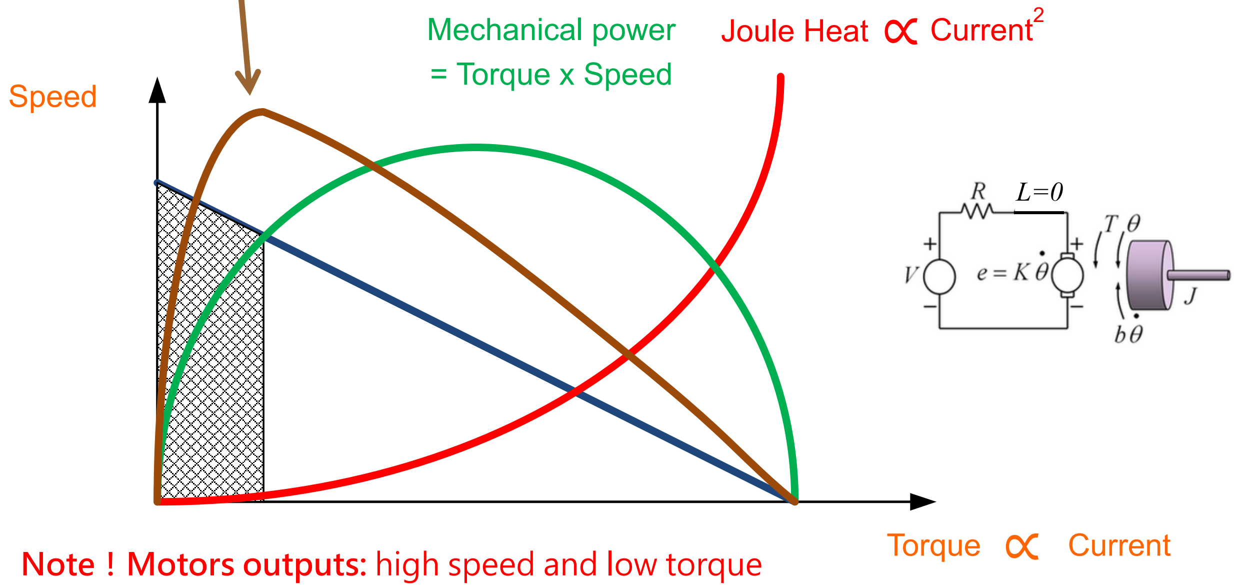
Brushed DC Motor -8

- GWS EM400

型號	測試電壓	無負載		瞬間啟動		尺寸		重量		價格 (NT$)
		電流 (安培)	速度 (轉速)	扭力 (克-公分)	電流 (安培)	軸心 (公厘)	外觀 (公厘)	公克	盎司	
CN12-R-XC	7.2V	0.28	25500	>130.0	<7.2	ϕ1.5x4.6	ϕ12x30	15	0.53	175
CN12-R-LC	2.4V	0.34	15200	>65.0	<7	ϕ1.5x4.6	ϕ12x30	15	0.53	175
CN12-B2C	4.5V	0.12	23700	>20	<1.6	ϕ1.0x3.4	ϕ12x10x15.4	5.6	0.20	175
CN12-B2C2	4.5V	0.12	23700	>20	<1.6	ϕ1.0x4.9	ϕ12x10x15.4	5.6	0.20	175
EM100	6.0V	0.36	14000	>310	<9.10	ϕ2.0x10.6	ϕ23.8x30.5	40	1.41	75
EM150	3.6V	0.48	12500	>240	<11	ϕ2.0x10.6	ϕ23.8x30.5	40	1.41	75
EM300	7.2V	1.6	34000	>570	<27	ϕ2.0x7.3	ϕ24.4x30.8	46	1.62	200
EM300H	7.2V	0.75	22950	>570	<21	ϕ2.0x7.3	ϕ24.4x30.8	46	1.62	200
EM350	6.0V	1.4	30500	>600	<36	ϕ2.0x7.3	ϕ24.4x30.8	46	1.62	200
EM400	7.2V	1.3	19200	>1172	<32	ϕ2.3x13.8	ϕ27.7x37.8	80.2	2.83	125
CN08-PLUS	4.5V	0.065	24500	>5.5	<0.46	ϕ1.0x1.9	ϕ8.0x6.0x14.5	3.4	0.12	150
CN10-PLUS	4.5V	0.05	17000	>8.5	<0.46	ϕ1.0x4.7	ϕ10x8.0x15	5	0.18	125

Brushed DC Motor -9

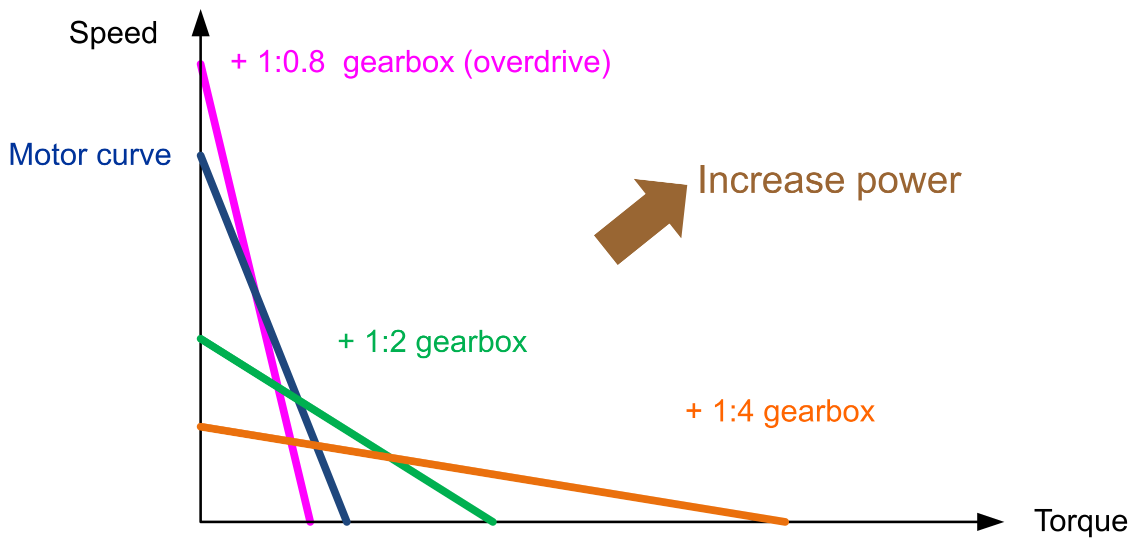
$$\text{Efficiency} = \frac{\text{Mechanical power}}{\text{Mechanical power + Joule Heat (= Electric power)}}$$



Note ! Motors outputs: high speed and low torque
If low speed and high torque needed: Add gear box
If both needed: Use a motor with higher power

Brushed DC Motor -10

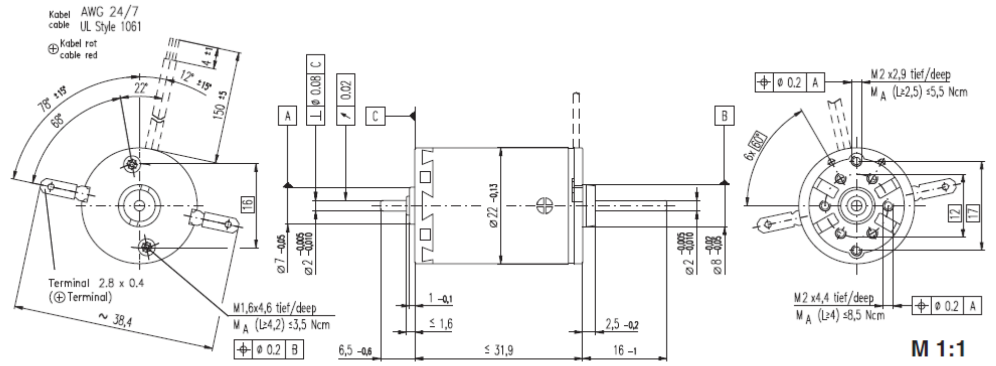
- DC Brushed Motor + gearbox
  - Adding gearbox: decreasing speed and increasing torque
  - Gearbox efficiency



Brushed DC Motor -11

A-max 22 ∅22 mm, Graphite Brushes, 6 Watt

maxon A-max



Stock program
Standard program
Special program (on request)

		Order Number											
	with terminals	110156	110158	110159	110160	110161	110162	110163	110164	110165	110166	110167	110168
	with cables	139848	353023	353024	231171	353025	353026	231174	353027	353028	353029	316659	353603
Motor Data													
Values at nominal voltage													
1 Nominal voltage	V	6.0	9.0	9.0	12.0	12.0	15.0	18.0	24.0	24.0	36.0	48.0	48.0
2 No load speed	rpm	9250	9710	8530	10200	9200	10100	9800	10500	8500	9650	9130	8220
3 No load current	mA	83.2	57.9	49.7	45.9	40.5	36.0	29.0	23.7	18.4	14.2	10.0	8.85
4 Nominal speed	rpm	5550	6370	5240	6990	5960	6880	6630	7430	5340	6500	5920	5020
5 Nominal torque (max. continuous torque)	mNm	5.82	6.52	6.76	6.77	6.82	6.87	6.94	6.97	7.07	7.00	6.91	7.02
6 Nominal current (max. continuous current)	A	1.06	0.816	0.741	0.664	0.602	0.529	0.433	0.350	0.287	0.214	0.150	0.138
7 Stall torque	mNm	16.1	20.4	18.7	22.8	20.4	22.7	22.3	24.3	19.5	21.9	20.1	18.5
8 Starting current	A	2.73	2.38	1.92	2.09	1.69	1.64	1.30	1.14	0.745	0.631	0.411	0.340
9 Max. efficiency	%	65	70	69	72	71	72	72	73	71	72	71	70
Characteristics													
10 Terminal resistance	Ω	2.20	3.78	4.69	5.74	7.12	9.15	13.8	21.0	32.2	57.1	117	141
11 Terminal inductance	mH	0.106	0.222	0.288	0.362	0.445	0.584	0.890	1.37	2.10	3.68	7.29	8.95
12 Torque constant	mNm / A	5.90	8.55	9.73	10.9	12.1	13.9	17.1	21.2	26.2	34.8	48.9	54.3
13 Speed constant	rpm / V	1620	1120	981	875	790	689	558	450	364	274	195	176
14 Speed / torque gradient	rpm / mNm	604	494	473	461	465	455	451	445	447	450	466	458
15 Mechanical time constant	ms	25.2	21.8	21.2	20.6	20.3	19.9	19.4	19.1	19.0	18.9	18.9	18.8
16 Rotor inertia	gcm²	3.98	4.22	4.28	4.26	4.17	4.17	4.11	4.11	4.07	4.00	3.88	3.92

Brushed DC Motor -12

Specifications

Thermal data
17 Thermal resistance housing-ambient 20 K / W
18 Thermal resistance winding-housing 6.0 K / W
19 Thermal time constant winding 10.1 s
20 Thermal time constant motor 540 s
21 Ambient temperature -30 ... +85°C
22 Max. permissible winding temperature +125°C

Mechanical data (sleeve bearings)
23 Max. permissible speed 9800 rpm
24 Axial play 0.05 - 0.15 mm
25 Radial play 0.012 mm
26 Max. axial load (dynamic) 1 N
27 Max. force for press fits (static) 80 N
(static, shaft supported) 440 N
28 Max. radial loading, 5 mm from flange 2.8 N

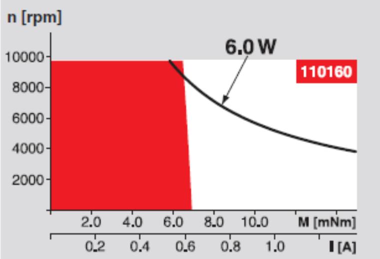
Mechanical data (ball bearings)
23 Max. permissible speed 9800 rpm
24 Axial play 0.05 - 0.15 mm
25 Radial play 0.025 mm
26 Max. axial load (dynamic) 3.3 N
27 Max. force for press fits (static) 45 N
(static, shaft supported) 440 N
28 Max. radial loading, 5 mm from flange 12.3 N

Other specifications
29 Number of pole pairs 1
30 Number of commutator segments 9
31 Weight of motor 54 g

Values listed in the table are nominal.
Explanation of the figures on page 49.

Option
Ball bearings in place of sleeve bearings

Operating Range



Comments

Continuous operation
In observation of above listed thermal resistance (lines 17 and 18) the maximum permissible winding temperature will be reached during continuous operation at 25°C ambient.
= Thermal limit.

Short term operation
The motor may be briefly overloaded (recurring).

Assigned power rating

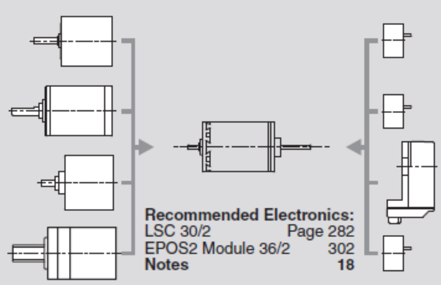
maxon Modular System Overview on page 16 - 21

Planetary Gearhead
∅22 mm
0.1 - 0.6 Nm
Page 222 / 223

Planetary Gearhead
∅22 mm
0.5 - 2.0 Nm
Page 224 / 225

Spur Gearhead
∅24 mm
0.1 Nm
Page 229

Spindle Drive
∅22 mm
Page 249 / 250



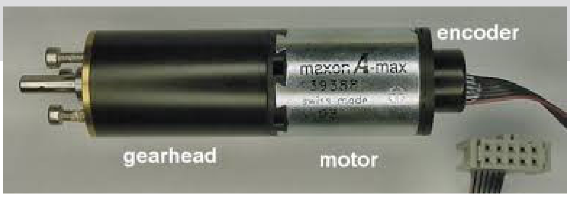
Recommended Electronics:
LSC 30/2 Page 282
EPOS2 Module 36/2 302
Notes 18

Encoder MR
32 CPT,
2 / 3 channels
Page 260

Encoder MR
128 / 256 / 512 CPT,
2 / 3 channels
Page 262

Encoder Enc
22 mm
100 CPT, 2 channels
Page 267

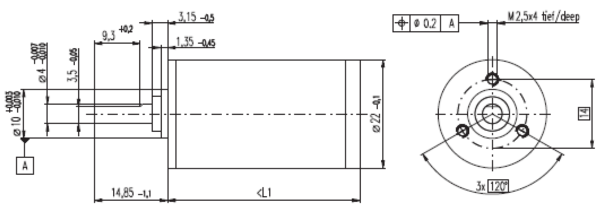
Encoder MEnc
∅13 mm
16 CPT, 2 channels
Page 275



Brushed DC Motor -13

Planetary Gearhead GP 22 A ∅22 mm, 0.5 - 1.0 Nm

maxon gear



M 1:1

Technical Data	
Planetary Gearhead	straight teeth
Output shaft	stainless steel, hardened
Bearing at output	ball bearing
Option	sleeve bearing
Radial play, 10 mm from flange	max. 0.2 mm
Axial play	max. 0.2 mm
Max. radial load, 10 mm from flange	70 N
Max. permissible axial load	100 N
Max. permissible force for press fits	100 N
Sense of rotation, drive to output	=
Recommended input speed	< 6000 rpm
Recommended temperature range	-20 ... +100°C
Extended area as option	-35 ... +100°C

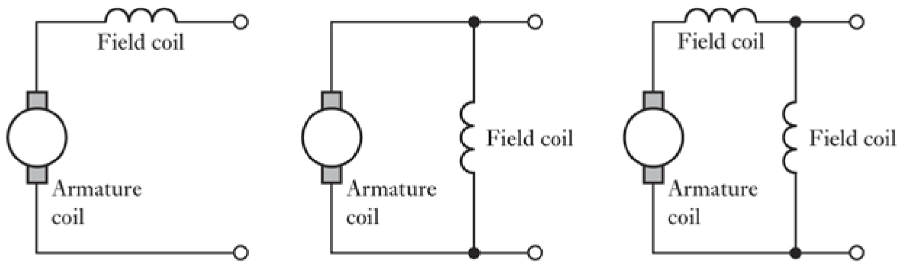
Stock program
Standard program
Special program (on request)

Order Number		134156	134158	134163	134168	134172	110340	134183	134186	134190	134195	134203
Gearhead Data												
1 Reduction		3.8 : 1	14 : 1	53 : 1	104 : 1	198 : 1	370 : 1	590 : 1	742 : 1	1386 : 1	1996 : 1	3189 : 1
2 Reduction absolute		15/4	225/16	3375/64	87723/845	50625/256	10556001/28561	59049/100	750375/1024	158340015/114244	285012027/142805	1594323/500
3 Max. motor shaft diameter	mm	4	4	4	3.2	4	3.2	4	4	3.2	3.2	4
Order Number		110337	134159	134164	134169	134173	134178	134184	134187	134193	134198	134204
1 Reduction		4.4 :1	16 : 1	62 : 1	109 : 1	231 : 1	389 : 1	690 : 1	867 : 1	1460 : 1	2102 : 1	3728 : 1
2 Reduction absolute		57/13	855/52	12825/208	2187/20	192375/832	263169/676	1121931/1625	2885625/3328	3947535/2704	7105563/3380	30292137/8125
3 Max. motor shaft diameter	mm	3.2	3.2	3.2	4	3.2	3.2	3.2	3.2	3.2	3.2	3.2
Order Number		134157	110338	134165	134170	134174	134180	134185	134188	134196	134200	134205
1 Reduction		5.4 : 1	19 : 1	72 : 1	128 : 1	270 : 1	410 : 1	850 : 1	1014 : 1	1538 : 1	2214 : 1	4592 : 1
2 Reduction absolute		27/5	3249/169	48735/676	41553/325	731025/2704	6561/16	531441/625	10965375/10816	98415/64	177147/80	14348907/3125
3 Max. motor shaft diameter	mm	2.5	3.2	3.2	3.2	3.2	4	2.5	3.2	4	4	2.5
Order Number			134160	134166	134171	134176	134179		134191	110341	134199	
1 Reduction			20 : 1	76 : 1	157 : 1	285 : 1	455 : 1		1068 : 1	1621 : 1	2458 : 1	
2 Reduction absolute			81/4	1215/16	19683/125	18225/64	5000211/10985		273375/256	601692057/371293	135005697/54925	
3 Max. motor shaft diameter	mm		4	4	2.5	4	3.2		4	3.2	3.2	
Order Number			134161	110339		134175	134181		134189	134194	134201	
1 Reduction			24 : 1	84 : 1		316 : 1	479 : 1		1185 : 1	1707 : 1	2589 : 1	
2 Reduction absolute			1539/65	185193/2197		2777895/8788	124659/260		41668425/35152	15000633/8788	3365793/1300	
3 Max. motor shaft diameter	mm		3.2	3.2		3.2	3.2		3.2	3.2	3.2	
Order Number			134162	134167		134177	134182		134192	134197	134202	
1 Reduction			29 : 1	89 : 1		333 : 1	561 : 1		1249 : 1	1798 : 1	3027 : 1	
2 Reduction absolute			729/25	4617/52		69255/208	2368521/4225		1038825/832	373977/208	63950067/21125	
3 Max. motor shaft diameter	mm		2.5	3.2		3.2	3.2		3.2	3.2	3.2	
4 Number of stages		1	2	3	3	4	4	4	5	5	5	5
5 Max. continuous torque	Nm	0.5	0.5	0.8	0.8	1.0	1.0	1.0	1.0	1.0	1.0	1.0
6 Intermittently permissible torque at gear output	Nm	0.8	0.8	1.2	1.2	1.6	1.6	1.6	1.6	1.6	1.6	1.6
7 Max. efficiency	%	84	70	59	59	49	49	49	42	42	42	42
8 Weight	g	42	55	68	68	81	81	81	94	94	94	94
9 Average backlash no load	°	1.0	1.2	1.6	1.6	2.0	2.0	2.0	2.0	2.0	2.0	2.0
10 Mass inertia	gcm²	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
11 Gearhead length L1*	mm	25.4	32.2	39.0	39.0	45.8	45.8	45.8	52.6	52.6	52.6	52.6

*for EC 20 flat L1 is - 2.8 mm, for EC 32 flat L1 is + 6.3 mm

Brushed DC Motor -14

- Brushed DC motors with field coils



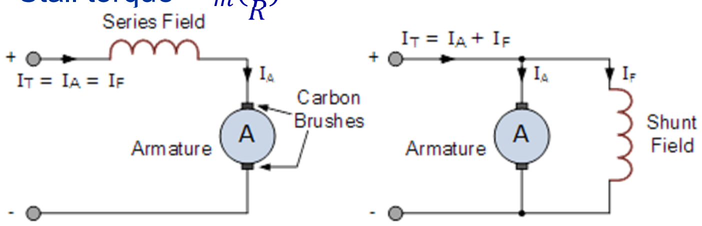
Series wound motor
- High starting torque
- High no-load speed

Shunt-wound motor
- Low starting torque
- Low no-load speed
- Good speed regulation

Compound motor

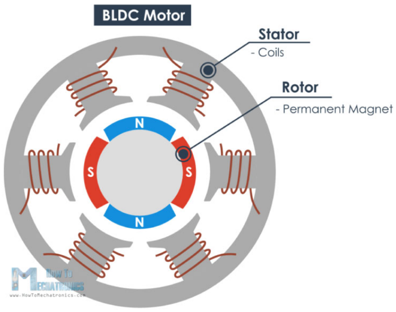
$$\tau = k_1 k_f i_f i_a = k_1 k_f {i_a}^2$$

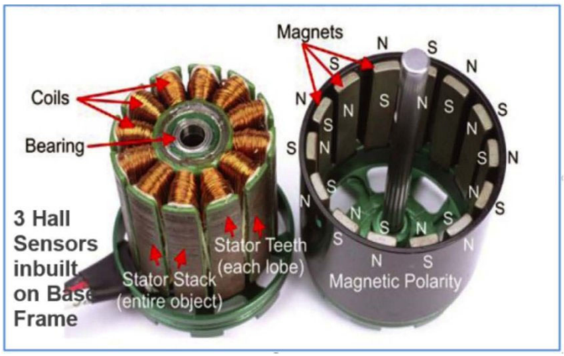
Stall torque $K_m(\frac{v}{R})^2$

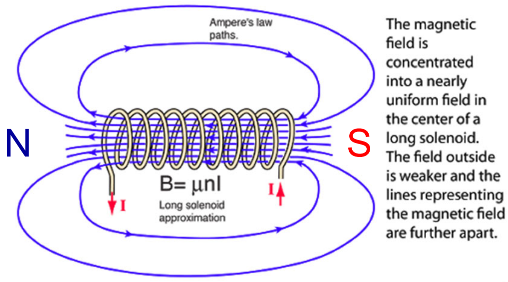


Brushless DC Motor -1

- Rotor
  - 2-8 pole pairs that alternates between N and S
- Stator
  - 6-24 pole pieces
- Phase
  - Number of individually controllable coils

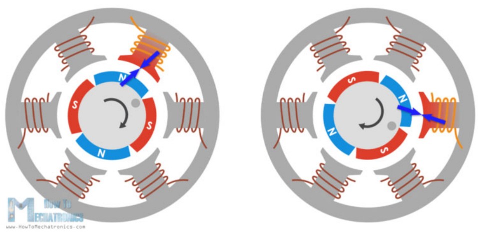


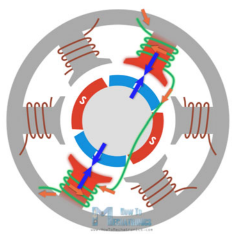


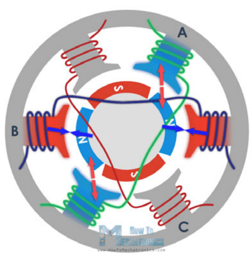


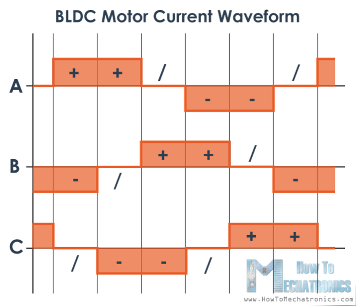
Brushless DC Motor -2

- Coil energizing methods
  - Single pole
    - 6 phases
  - Two poles
    - 3 phases
    - Double attraction force
  - Four poles
    - 3 phases
    - Attraction & Repelling



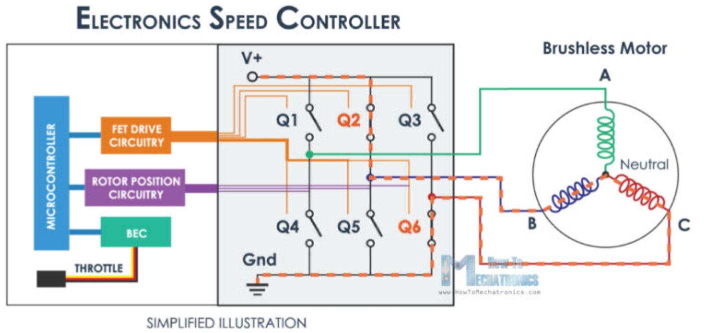


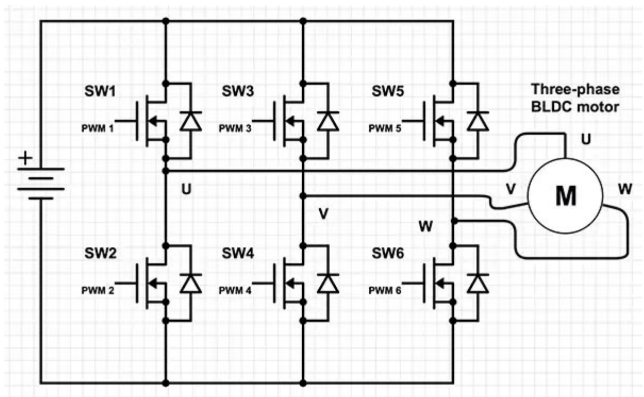




Brushless DC Motor -3

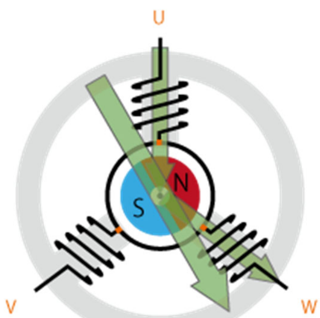
- Commutation sequence: each sequence has
  - One winding energized positive (current into the winding)
  - One winding energized negative (current out of the winding)
  - One winding non-energized

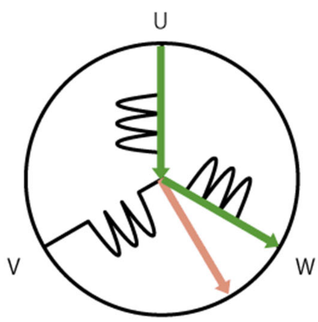




Brushless DC Motor -4

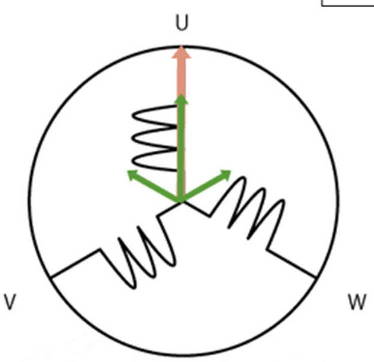
- Commutation sequence
  - Digital control





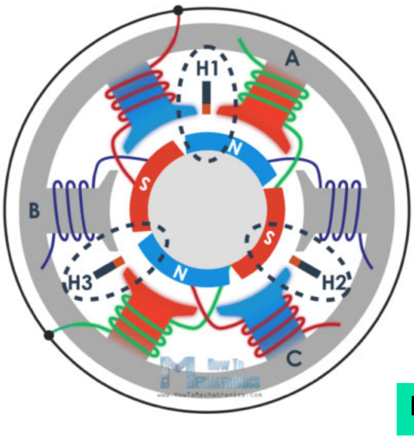
Energizing Mode	Energized Phase	Resultant Flux
1	U→W	
2	U→V	
3	W→V	
4	W→U	
5	V→U	
6	V→W	

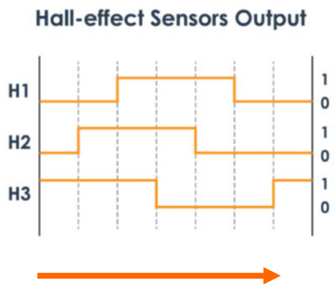
  - Sinusoidal control



Brushless DC Motor -5

- How do we know when to activate which phase?
  - Method 1: Using hall-effect sensors

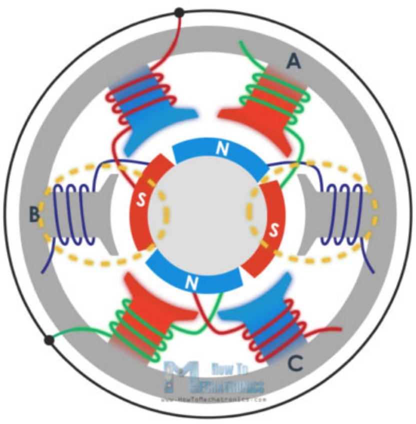


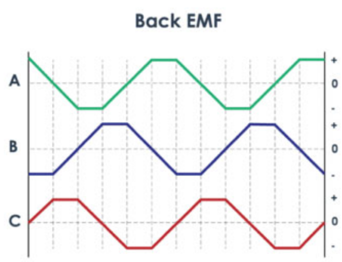


H1	0	0	1	1	1	0
H2	0	1	1	1	0	0
H3	1	1	1	0	0	0

Brushless DC Motor -6

- How do we know when to activate which phase?
  - Method 2: Sensing the back EMF of the coil that is not active

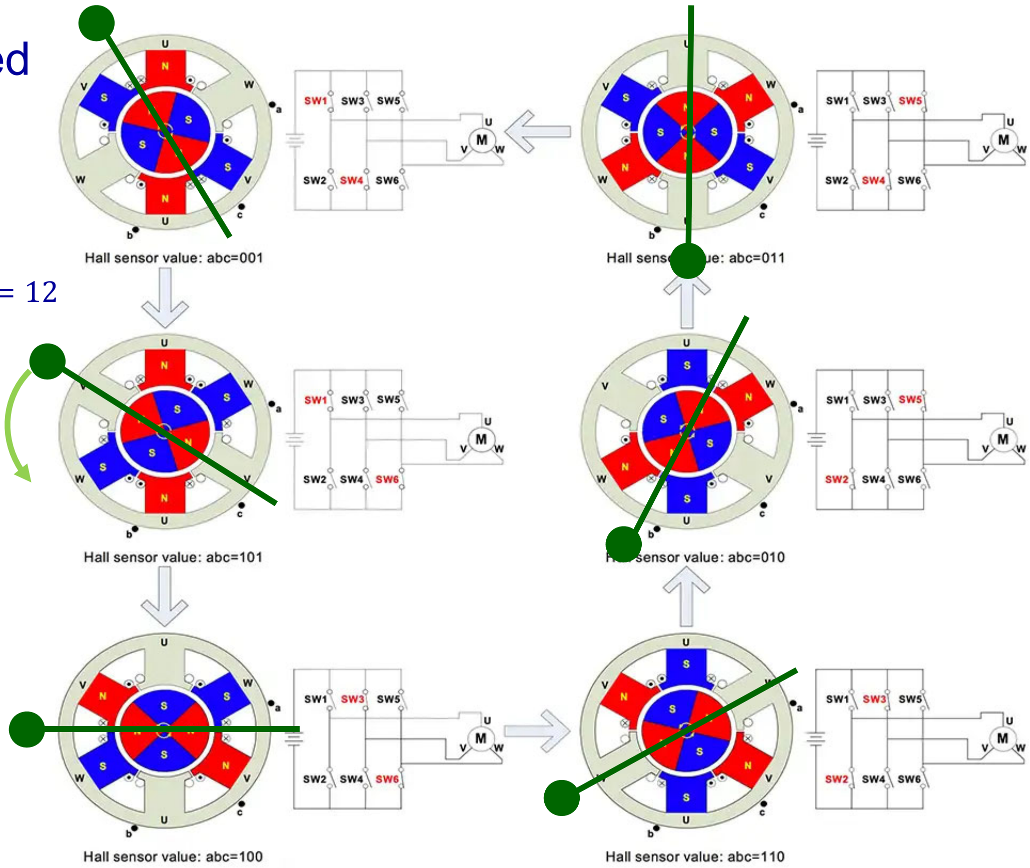




Brushless DC Motor -7

- Sensored motor

$S = 2pN_{poles}$
$= 2 \times 3 \times 2 = 12$

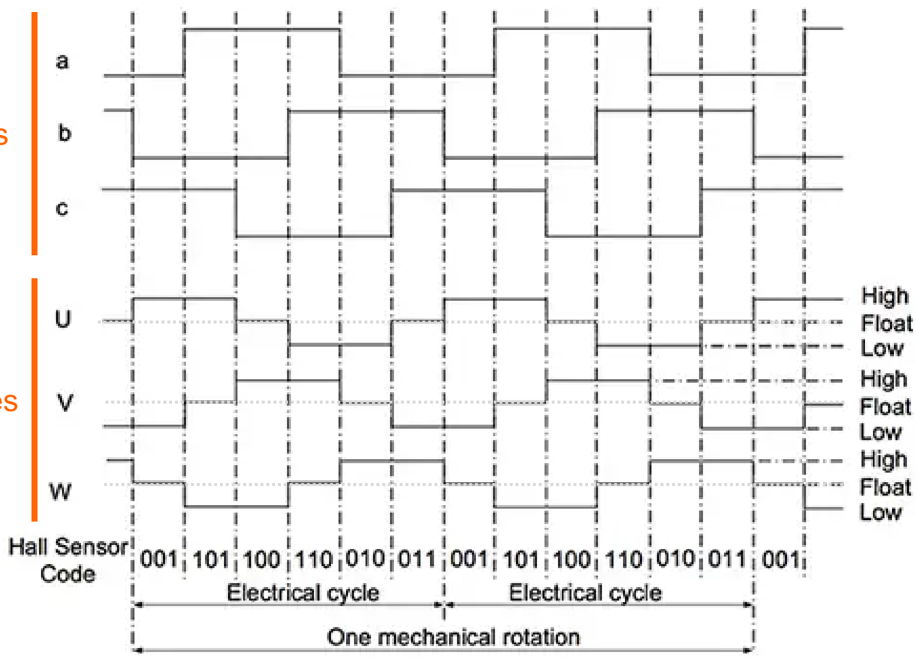


Brushless DC Motor -8

- Sensored motor

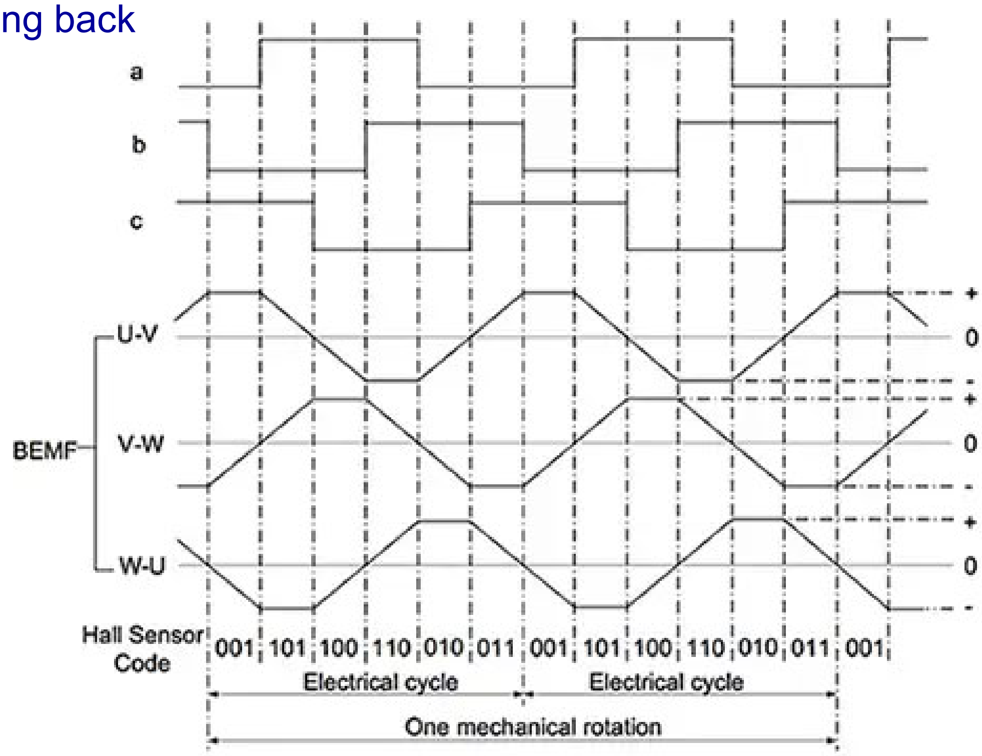
Hall sensor readings

Motor drives



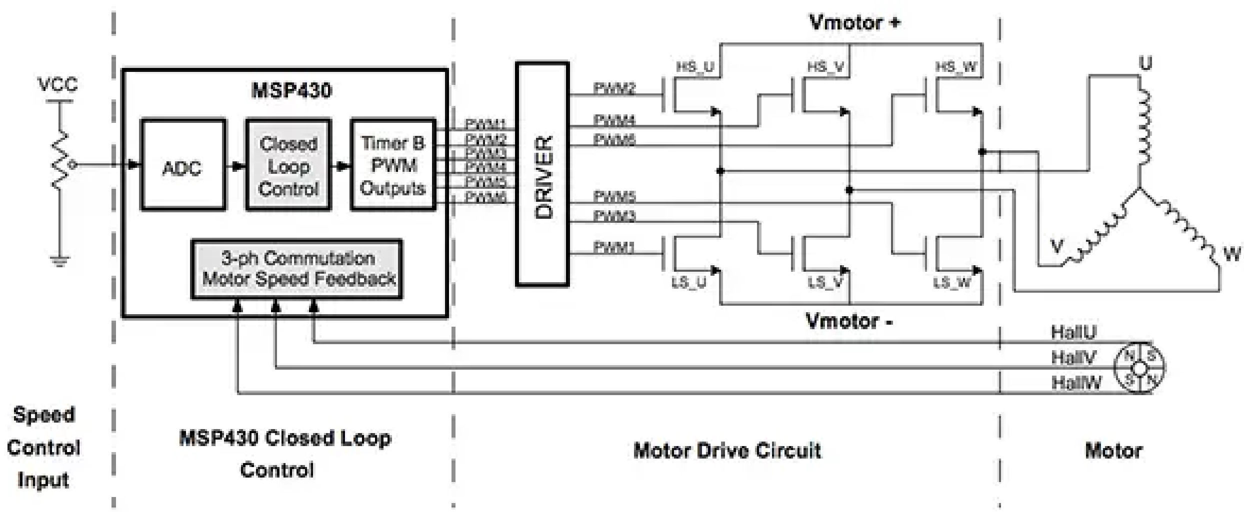
Brushless DC Motor -9

- Sensorless motor
  - Monitoring back EMF



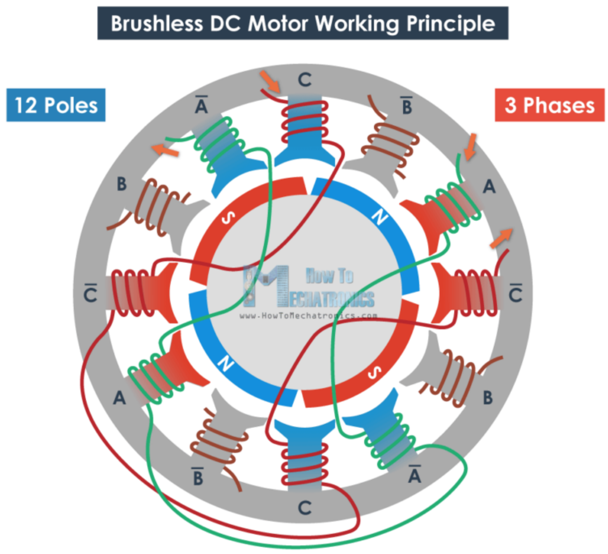
Brushless DC Motor -10

- Circuit example



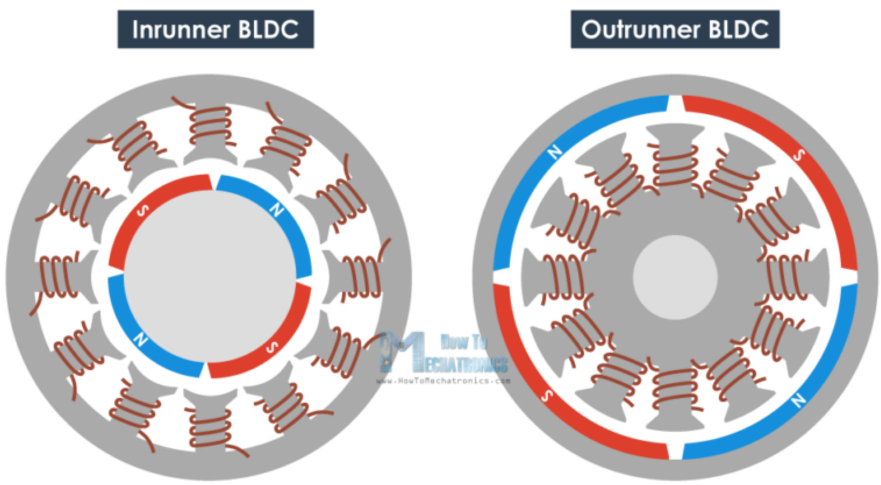
Brushless DC Motor -11

- Increasing the number of poles of the both the rotor and the stator
  - Still three-phase
  - The number of intervals will increase in order to complete a full cycle

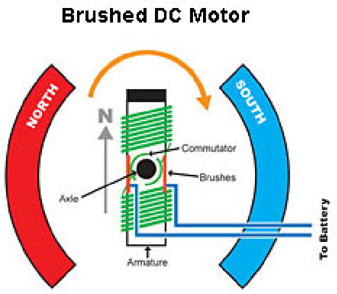


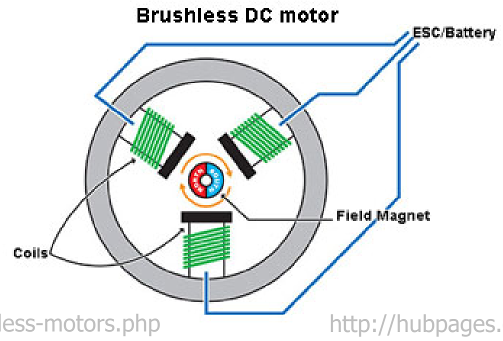
Brushless DC Motor -12

- BLDC types
  - Inrunner vs. outrunner

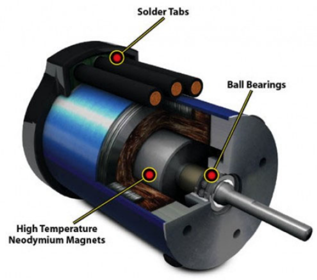


Brushed vs. Brushless DC Motors -1





http://www.thinkrc.com/faq/brushless-motors.php



http://hubpages.com/games-hobbies/whats-the-difference-between-brushed-brushless-rc-motors

Brushed DC Motor	Brushless DC Motor
Simple and inexpensive control No controller is required for fixed speeds Operates in extreme environments	High output power to size ratio High speed range Quiet acoustically and electrically Safe in explosive environment Easy to cool
Periodic maintenance is required Brush friction & arcing	Control is complex (electronic commutation) Expensive

Brushed vs. Brushless DC Motors -2

- Motor comparison

TABLE 1: COMPARING A BLDC MOTOR TO A BRUSHED DC MOTOR

Feature	BLDC Motor	Brushed DC Motor
Commutation	Electronic commutation based on Hall position sensors.	Brushed commutation.
Maintenance	Less required due to absence of brushes.	Periodic maintenance is required.
Life	Longer.	Shorter.
Speed/Torque Characteristics	Flat – Enables operation at all speeds with rated load.	Moderately flat – At higher speeds, brush friction increases, thus reducing useful torque.
Efficiency	High – No voltage drop across brushes.	Moderate.
Output Power/ Frame Size	High – Reduced size due to superior thermal characteristics. Because BLDC has the windings on the stator, which is connected to the case, the heat dissipation is better.	Moderate/Low – The heat produced by the armature is dissipated in the air gap, thus increasing the temperature in the air gap and limiting specs on the output power/frame size.
Rotor Inertia	Low, because it has permanent magnets on the rotor. This improves the dynamic response.	Higher rotor inertia which limits the dynamic characteristics.
Speed Range	Higher – No mechanical limitation imposed by brushes/commutator.	Lower – Mechanical limitations by the brushes.
Electric Noise Generation	Low.	Arcs in the brushes will generate noise causing EMI in the equipment nearby.
Cost of Building	Higher – Since it has permanent magnets, building costs are higher.	Low.
Control	Complex and expensive.	Simple and inexpensive.
Control Requirements	A controller is always required to keep the motor running. The same controller can be used for variable speed control.	No controller is required for fixed speed; a controller is required only if variable speed is desired.

Brushed vs. Brushless DC Motors -3

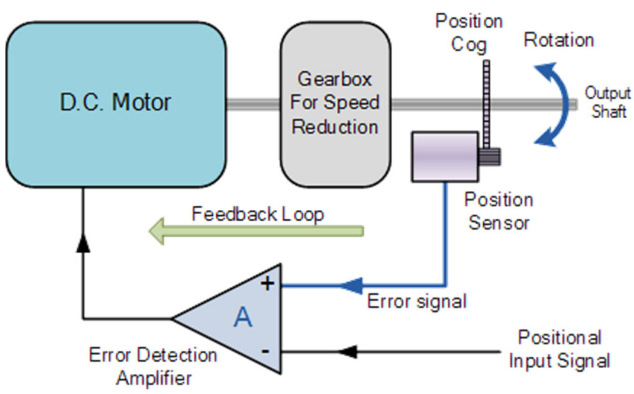
- Motor comparison

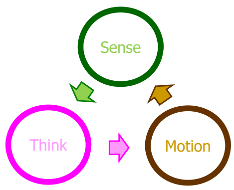
TABLE 2: COMPARING A BLDC MOTOR TO AN INDUCTION MOTOR

Features	BLDC Motors	AC Induction Motors
Speed/Torque Characteristics	Flat – Enables operation at all speeds with rated load.	Nonlinear – Lower torque at lower speeds.
Output Power/ Frame Size	High – Since it has permanent magnets on the rotor, smaller size can be achieved for a given output power.	Moderate – Since both stator and rotor have windings, the output power to size is lower than BLDC.
Rotor Inertia	Low – Better dynamic characteristics.	High – Poor dynamic characteristics.
Starting Current	Rated – No special starter circuit required.	Approximately up to seven times of rated – Starter circuit rating should be carefully selected. Normally uses a Star-Delta starter.
Control Requirements	A controller is always required to keep the motor running. The same controller can be used for variable speed control.	No controller is required for fixed speed; a controller is required only if variable speed is desired.
Slip	No slip is experienced between stator and rotor frequencies.	The rotor runs at a lower frequency than stator by slip frequency and slip increases with load on the motor.

RC Servo Motor -1

- Characteristics
  - Swing motion
  - Gearbox, motor, potentiometer, control circuit
  - Feedback controlled





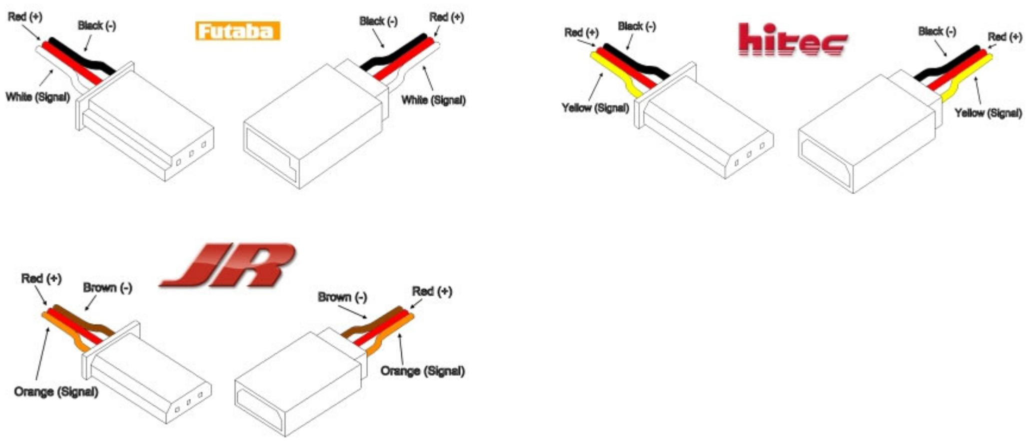
FUTABA S3003

資料來源：http://www.societyofrobots.com/actuators_waterproof_servo.shtml

FUTABA BLS351

RC Servo Motor -2

- 3 pin wiring
  - Fool-proof design
  - Middle pin: power supply (Vcc, red)
  - Ground pin (black), signal (white or yellow)



RC Servo Motor -3

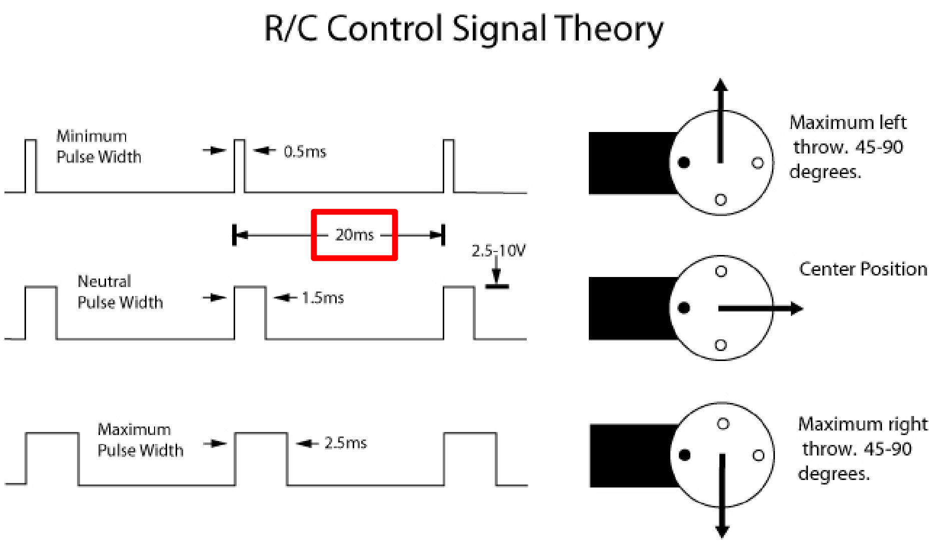
- Controlled using PWM (Pulse Width Modulation)

Duty cycle

2.5%

7.5%

12.5%



The minimum and maximum pulse width for different manufacturers can vary considerably; however, the neutral position is generally quite near 1.5ms regardless of manufacturer. Typical variance for the minimum pulse width is from 0.5ms to 0.8ms, and the typical variance for the maximum pulse width is from 2.5ms to 3.0ms. The frequency of the signal is generally near 50Hz; however, it can range from 30Hz to 200Hz. The output voltage can vary from 2.5V to as much as 10V.

資料來源：http://www.mitchr.me/SS/batteriesRequired/RCcontrolTheory/index.html

RC Servo Motor -4

- Some examples

standard

S3003 Standard

FUTM0031

Volts	Torque	Speed
4.8V	44 oz-in (3.2 kg/cm)	0.23 sec/60°
6.0V	57 oz-in (4.1 kg/cm)	0.19 sec/60°

Dimensions	Weight
1-9/16 x 13/16 x 1-7/16 in (40 x 20 x 36 mm)	1-5/16 oz (37 g)
	3P

mini

S3111 Micro Servo-J

FUTM0047

Volts	Torque	Speed
4.8V	8.3 oz-in (0.6 kg/cm)	0.12 sec/60°
6.0V	n/a	n/a

Dimensions	Weight
7/8 x 7/16 x 13/16 in (22 x 11 x 20 mm)	1/4 oz (6.3 g)
	3P

large

S3306MG HT/HS 1/5 Scale

FUTM0021

Volts	Torque	Speed
4.8V	267 oz-in (19.2 kg/cm)	0.20 sec/60°
6.0V	333 oz-in. (24.0 kg/cm)	0.16 sec/60°

Dimensions	Weight
2-5/8 x 1-3/16 x 2-1/4 in (66 x 30 x 57 mm)	4-7/16 oz (126 g)
	2BB, WP, MG, 3P

High-end

BLS157HV Ultra-Torque

FUTM0751

Volts	Torque	Speed
6.0V	431 oz-in (31.1 kg/cm)	0.14 sec/60°
7.4V	514 oz-in (37 kg/cm)	0.11 sec/60°

Dimensions	Weight
1-9/16 x 13/16 x 1-7/16 in (40 x 20 x 37 mm)	2.7 oz (77 g)
HV	2BB, HG, WP, BLS, MCC

BB = Ball Bearing • MG = Metal Gear • HG = Hybrid Gear • WP = Water Protected • BLS = Brushless Motor • MCC = Metal Center Case

RC Servo Motor -5

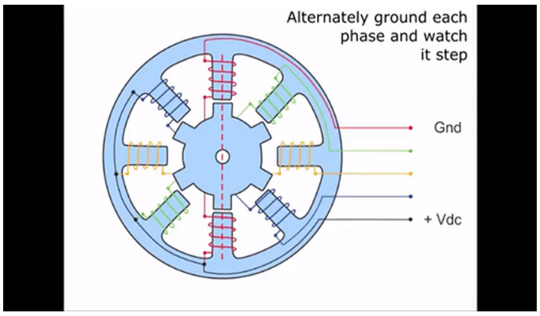
- GWS S03T-2BB

型號	價格 (NT$)			尺寸 (長 x 寬 x 高) 公厘 / 英吋	重量		4.8V			6V		
							速度 (秒/60°)	扭力		速度 (秒/60°)	扭力	
	STD	2BB	MG		公克	盎司		公斤-公分	盎司-英吋		公斤-公分	盎司-英吋
S03N	250	300	500	39.5x20.0x35.6 1.56x0.79x1.40	41(2BB) 64(MG)	1.45(2BB) 2.26(MG)	0.23	3.4	47	0.18	4.0	56
S03NF	250	300	500				0.18	2.8	39	0.15	3.2	44
S03NXF	250	300	500				0.15	2.2	31	0.12	2.5	34
S03T	250	300		39.5x20.0x39.5 1.56x0.79x1.56	46	1.62	0.33	7.2	100	0.27	8.0	111
S03TF	250	300					0.27	5.80	81	0.22	6.5	90
S03TXF	250	300					0.21	5.00	69	0.17	6.2	86
S03T-FET 2BBMG			525	39.5x20.0x39.5 1.56x0.79x1.56	73	2.57	0.32	8.0	110	0.28	9.0	125
S03T 2BBMG			500				0.33	7.4	103	0.28	8.0	111
S03TF 2BBMG			500				0.27	6.00	83	0.22	7.0	97
S03TXF 2BBMG			500				0.21	5.60	78	0.17	6.4	89

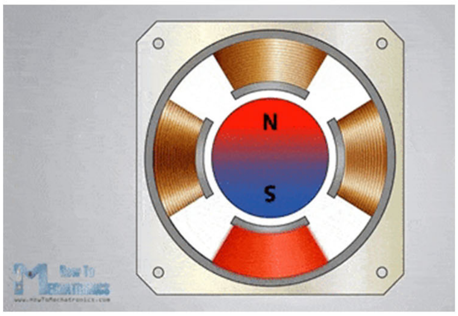
Stepper Motors -1

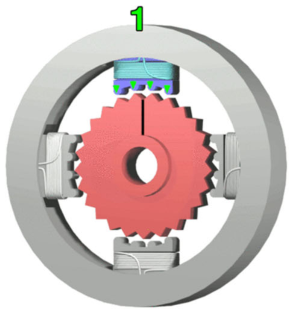
- Definition
  - A device that produces rotation through equal angles (i.e. the steps)
- Characteristics
  - Open-loop control

Variable reluctance



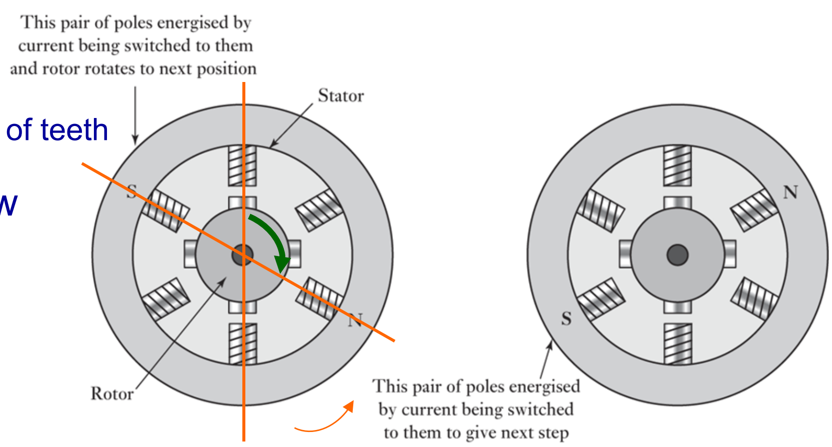
Permanent magnet





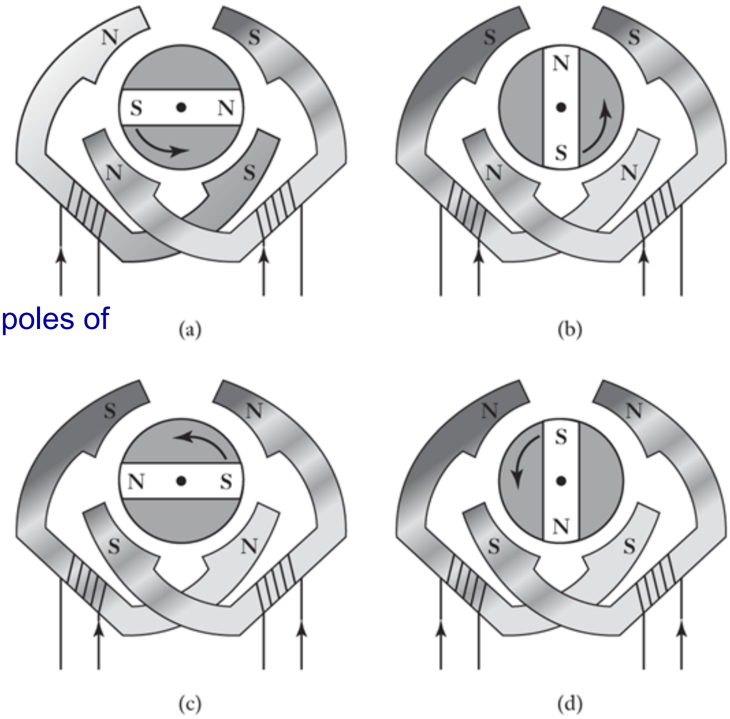
Stepper Motors -2

- Variable reluctance stepper
  - Rotor: soft steel
  - Fewer poles on the rotor than on the stator
  - Number of steps per revolution
    - $S = pN_{teeth}$
      - p: phases
      - N_{teeth}: number of teeth
  - Coils ccw → rotor cw
  - Example
    - $S = 3 * 4 = 12$



Stepper Motors -3

- Permanent magnet stepper
  - Number of steps per revolution
    - $S = 2pN_{poles}$
      - p: phases
      - N_{poles}: number of poles of the rotor
  - Example
    - 2-phase, $p = 2$
    - A stator with 4 poles
    - $N_{poles} = 1$
    - $S = 4$



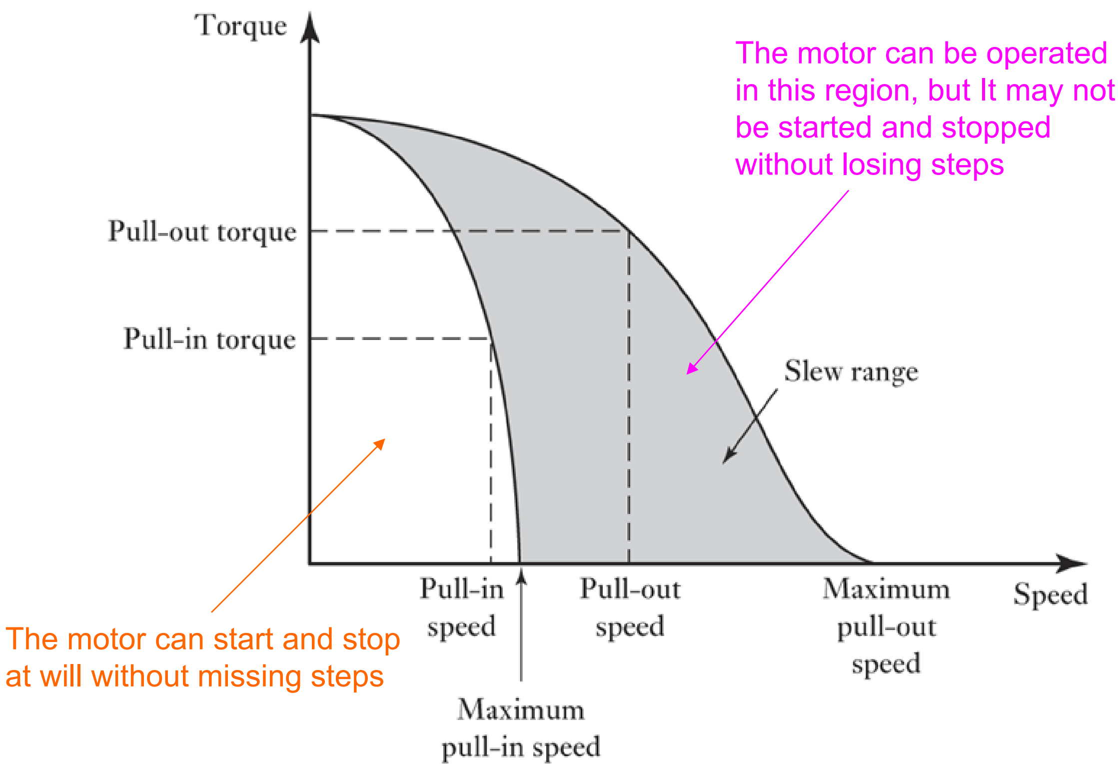
Stepper Motors -4

- Specifications
  - Phase
    - Number of independent winding on the stator
  - Step angle
    - The angle through which the rotor rotates for one switching change for the stator coils
  - Holding torque
    - The maximum torque tat can be applied to a powered motor without moving it from the rest position and causing spindle rotation
  - Pull-in torque
    - The maximum torque against which a motor will start, for a given pulse rate, and reach synchronism without losing a step

Stepper Motors -5

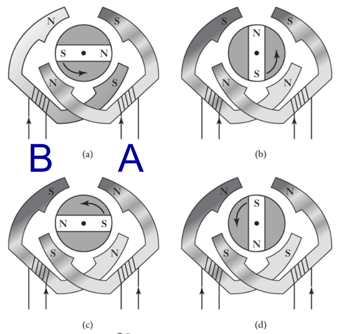
- Pull-out torque
  - The maximum torque that can be applied to a motor, running at a given stepping rate, without losing synchronism
- Pull-in rate
  - The maximum switching rate at which a loaded motor can start without losing a step
- Pull-out rate
  - The switching rate at which a loaded motor will remain in synchronism as the switching rate is reduced
- Slew range
  - The range of switching rates between pull-in and pull-out within which the motor runs in synchronism but cannot start up or reverse

Stepper Motors -6



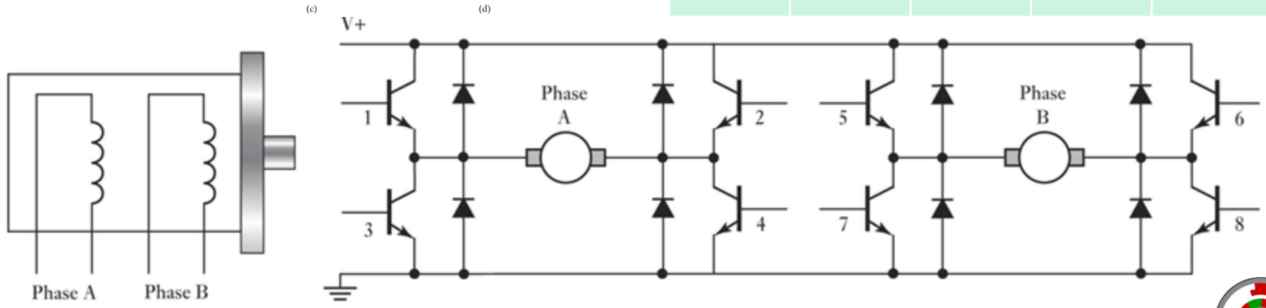
Stepper Motors -7

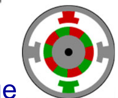
- Two-phase motor control
  - Bi-polar – 4 connecting wires, full-stepping



Full-stepping

step	transistor			
	1 & 4	2 & 3	5 & 8	6 & 7
1	ON	OFF	ON	OFF
2	ON	OFF	OFF	ON
3	OFF	ON	OFF	ON
4	OFF	ON	ON	OFF

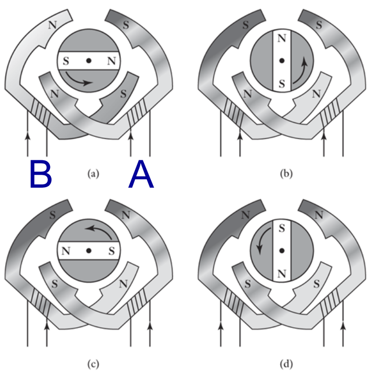




P.S. Wave drive: only one phase is actuated at a time, less torque

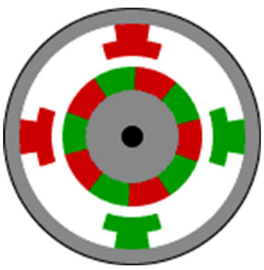
Stepper Motors -8

- Two-phase motor control
  - Bi-polar – 4 connecting wires, half-stepping
    - Same circuit, different actuation sequence



Half-stepping

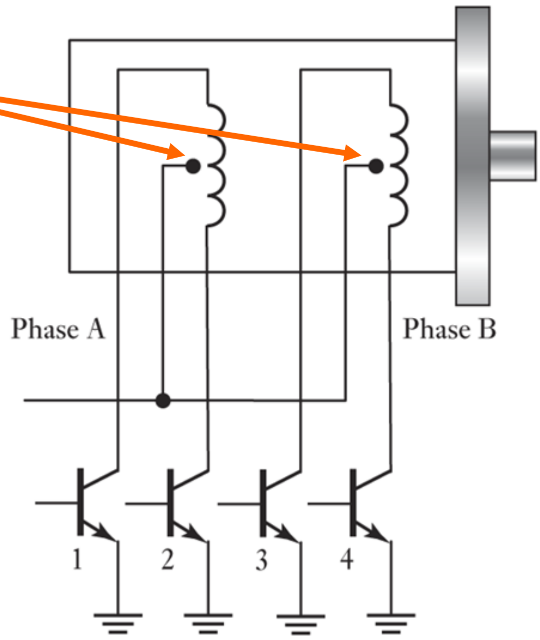
step	transistor			
	1 & 4	2 & 3	5 & 8	6 & 7
1	ON	OFF	ON	OFF
2	ON	OFF	OFF	OFF
3	ON	OFF	OFF	ON
4	OFF	OFF	OFF	ON
5	OFF	ON	OFF	ON
6	OFF	ON	OFF	OFF
7	OFF	ON	ON	OFF
8	OFF	OFF	ON	OFF



- "mini-stepping" – applying different currents to the coils

Stepper Motors -9

- Four-phase motor control
  - Unipolar – 6 connecting wires
    - Each coil has a center-tap
    - Only need 4 transistors



Full-stepping

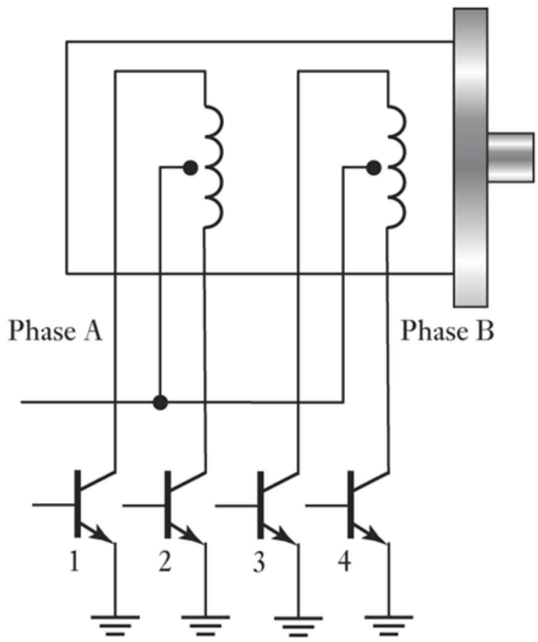
step	transistor			
	1	2	3	4
1	ON	OFF	ON	OFF
2	ON	OFF	OFF	ON
3	OFF	ON	OFF	ON
4	OFF	ON	ON	OFF

Stepper Motors -10

- Four-phase motor control
  - Unipolar – 6 connecting wires

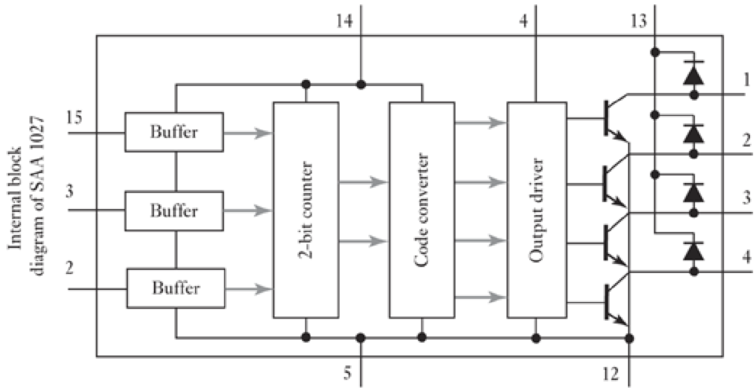
Half-stepping

step	transistor			
	1 & 4	2 & 3	5 & 8	6 & 7
1	ON	OFF	ON	OFF
2	ON	OFF	OFF	OFF
3	ON	OFF	OFF	ON
4	OFF	OFF	OFF	ON
5	OFF	ON	OFF	ON
6	OFF	ON	OFF	OFF
7	OFF	ON	ON	OFF
8	OFF	OFF	ON	OFF



Stepper Motors -11

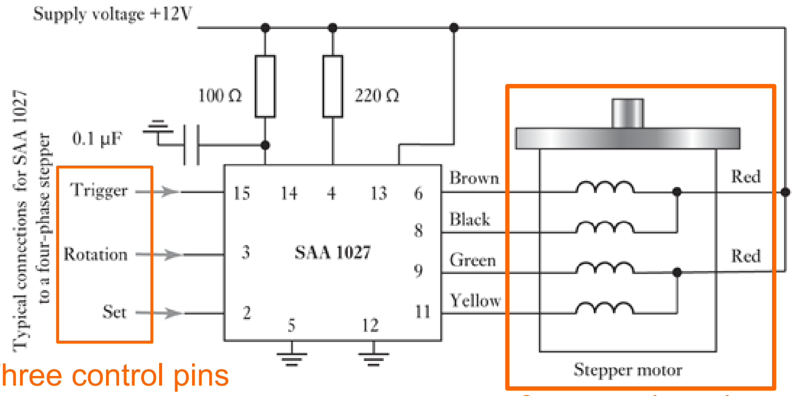
- Circuit example



(Low-to-high: change state)

(High-ccw; Low-cw)

(Enable)

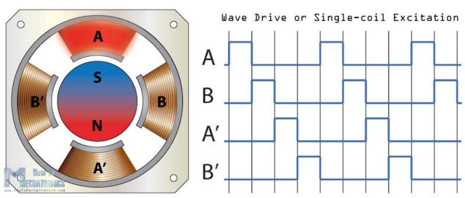


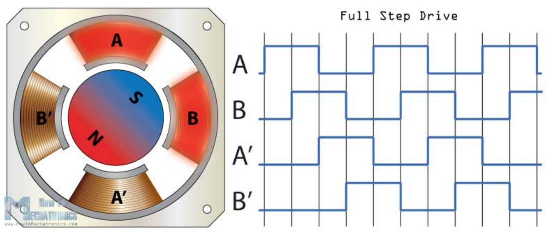
Three control pins

6 connecting wires

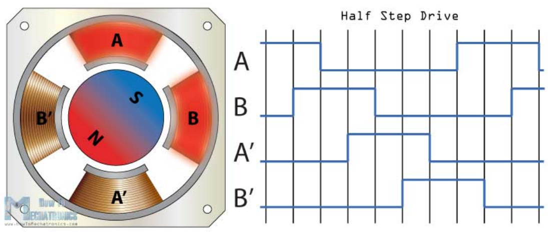
Stepper Motors -12

- Permanent magnet stepper
  - Full-stepping

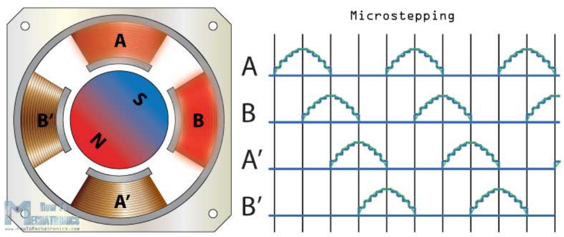




  - Half-stepping



  - Micro-stepping
    - Current control: sine wave



End

- Questions?