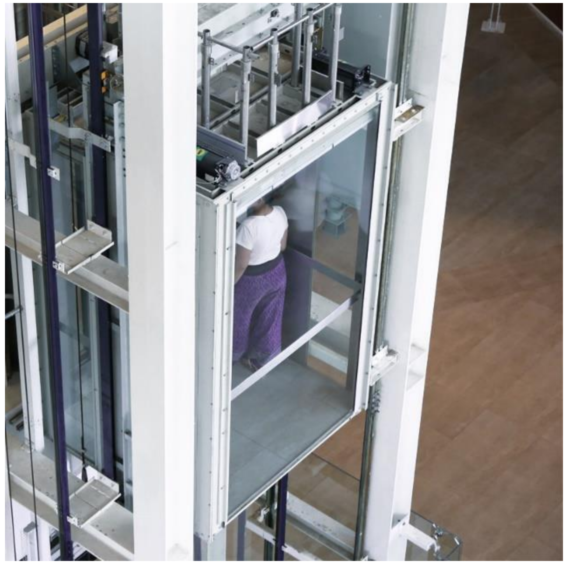
Aalto-yliopisto
Aalto-universitetet
Aalto University

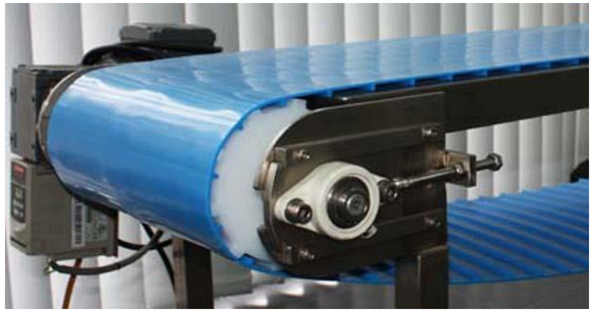
DC and Stepper motors

KON-C2004 Mechatronics Basics

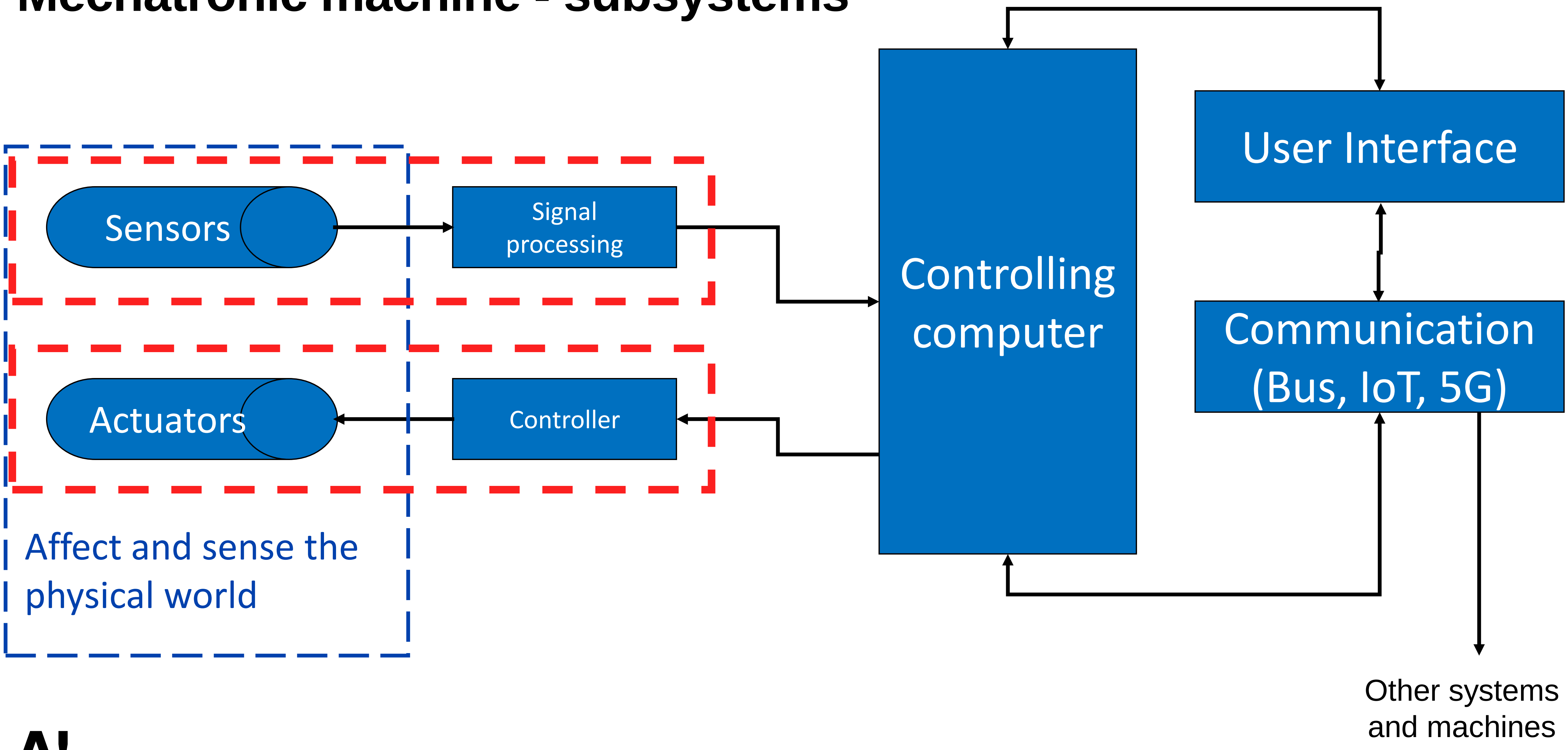
Raine Viitala 24.10.2024

Applications





Mechatronic machine - subsystems



A!

Learning outcomes today

After the lecture, student should

1. Understand the operating principle of brushed DC motors and stepper motors
2. Know simple mathematical models governing the DC motor operation
3. Know the control strategies of both motor types
4. Know the limitations of both motor types

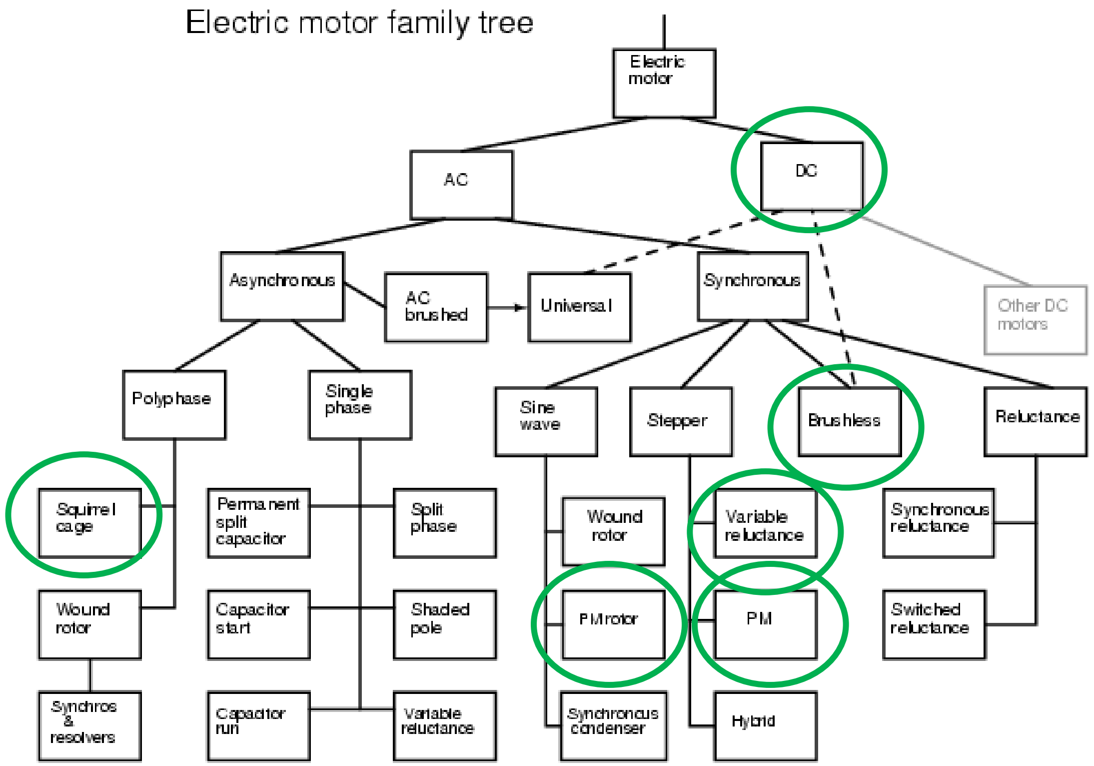
Electric motors

DC

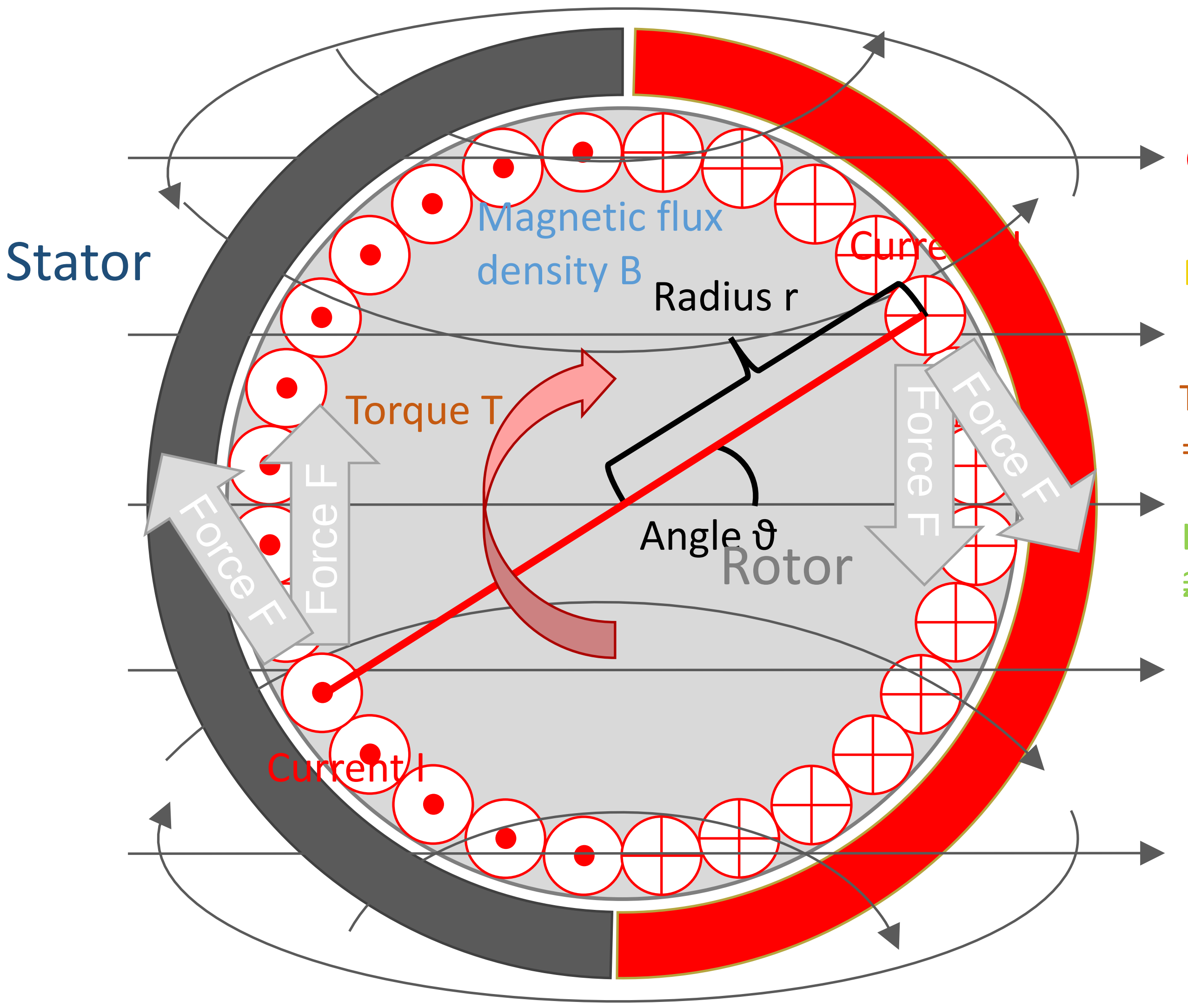
- Brushed
- Brushless

AC

- Synchronous
  - Permanent magnet rotor
  - Field excitation
  - Reluctance
- Asynchronous (Induction)
  - Squirrel cage
  - Wound rotor



Generic motor based on Lorentz force



Magnetic flux density B

Current I

Length l

Number of turns N

Force $F = Bl I$

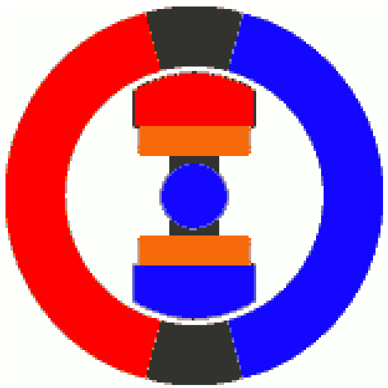
Torque $T = 2rF\cos(\vartheta)$

$= 2NrBlI = K_t I$

Induced voltage $= Blv$

$= 2NBlv = 2NBlr\omega = K_e\omega$

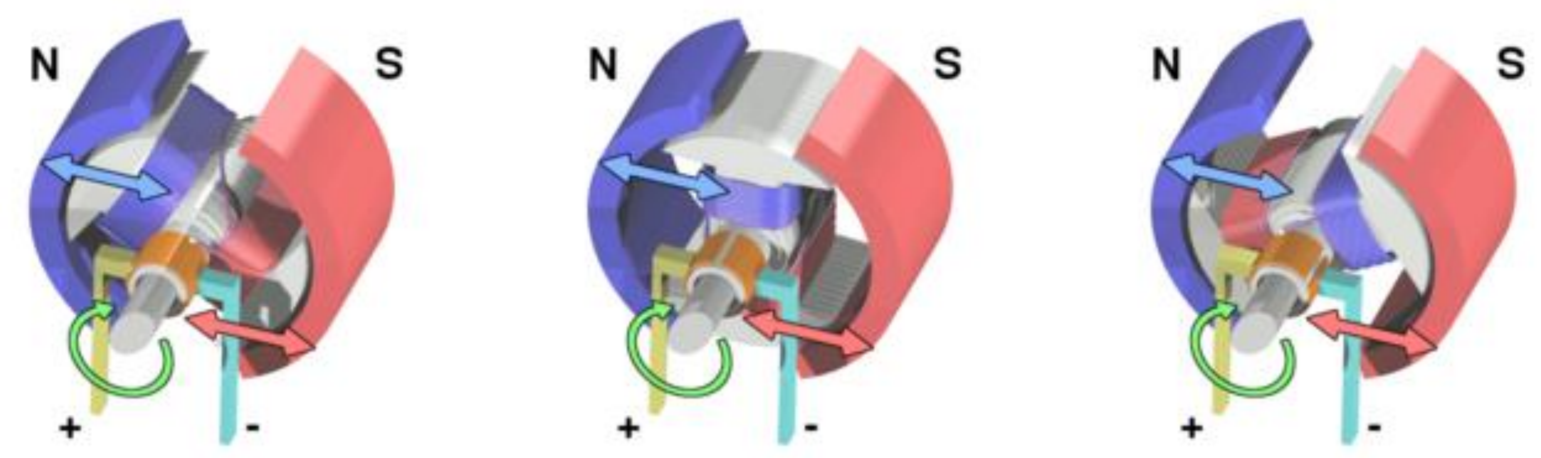
DC motor working principle



http://www.pcbheaven.com/wikipages/How_DC_Motors_Work/

Simple two pole example

- In practise motors have 2-8 poles



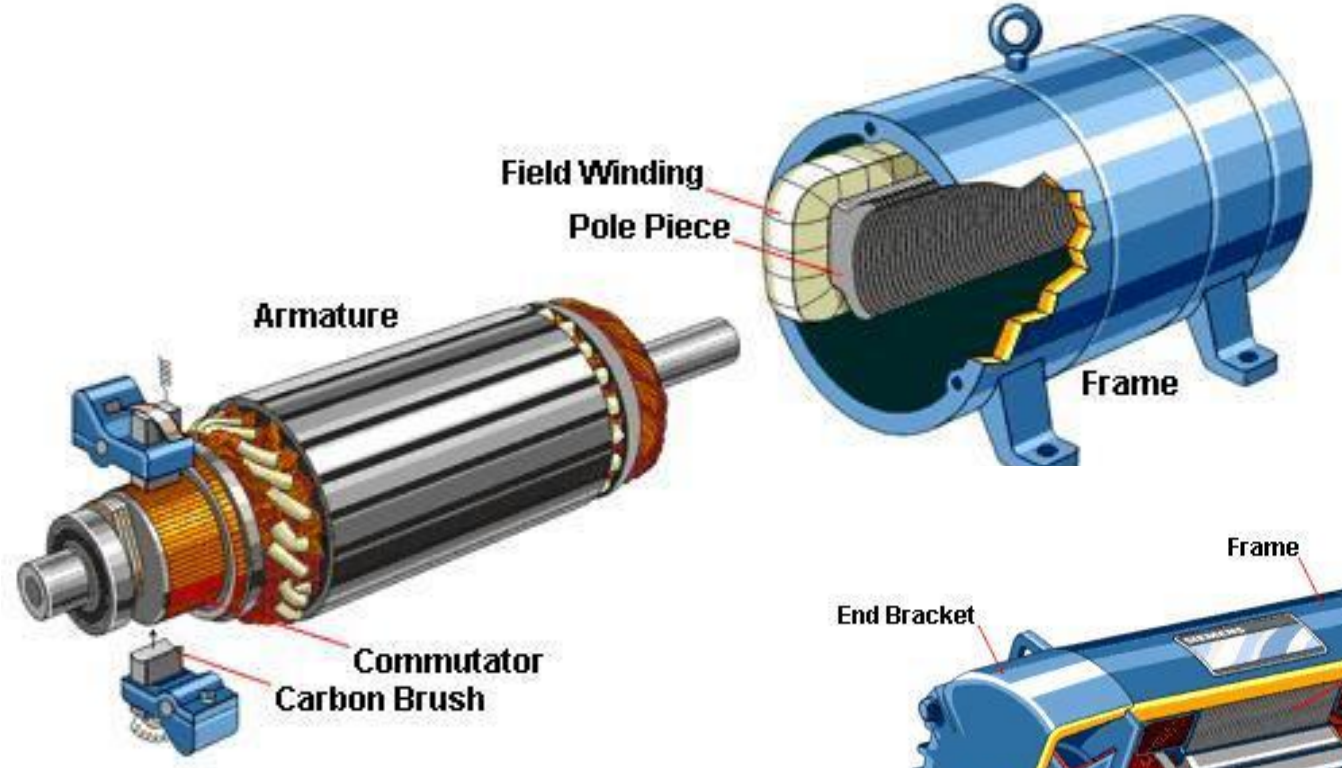
https://en.wikipedia.org/wiki/Brushed_DC_electric_motor

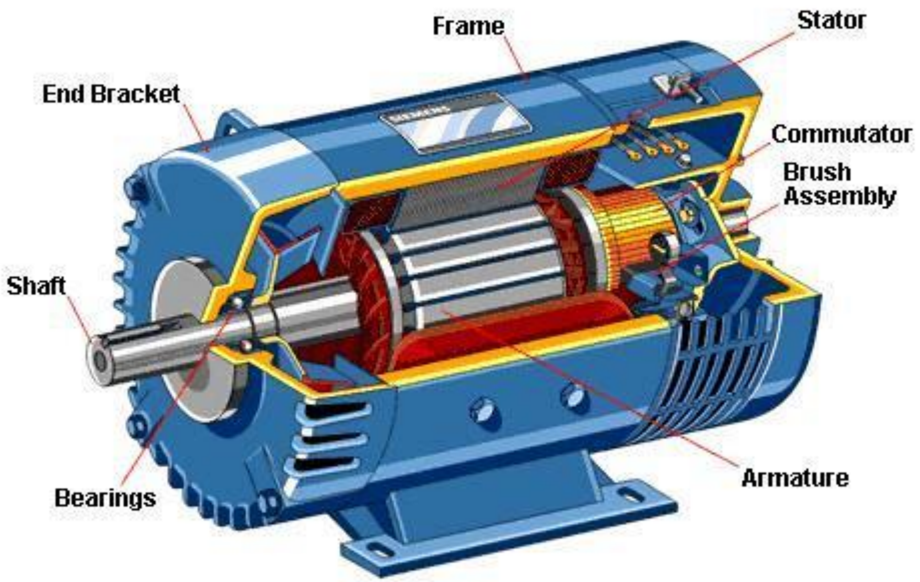
A!

Lecture task

- Discuss in groups of 2 - 4 about the generic motor model based on Lorentz law.
  - Make sure your colleague understands it – teach it!
- Make notes what was unclear – I will try to answer after the task.

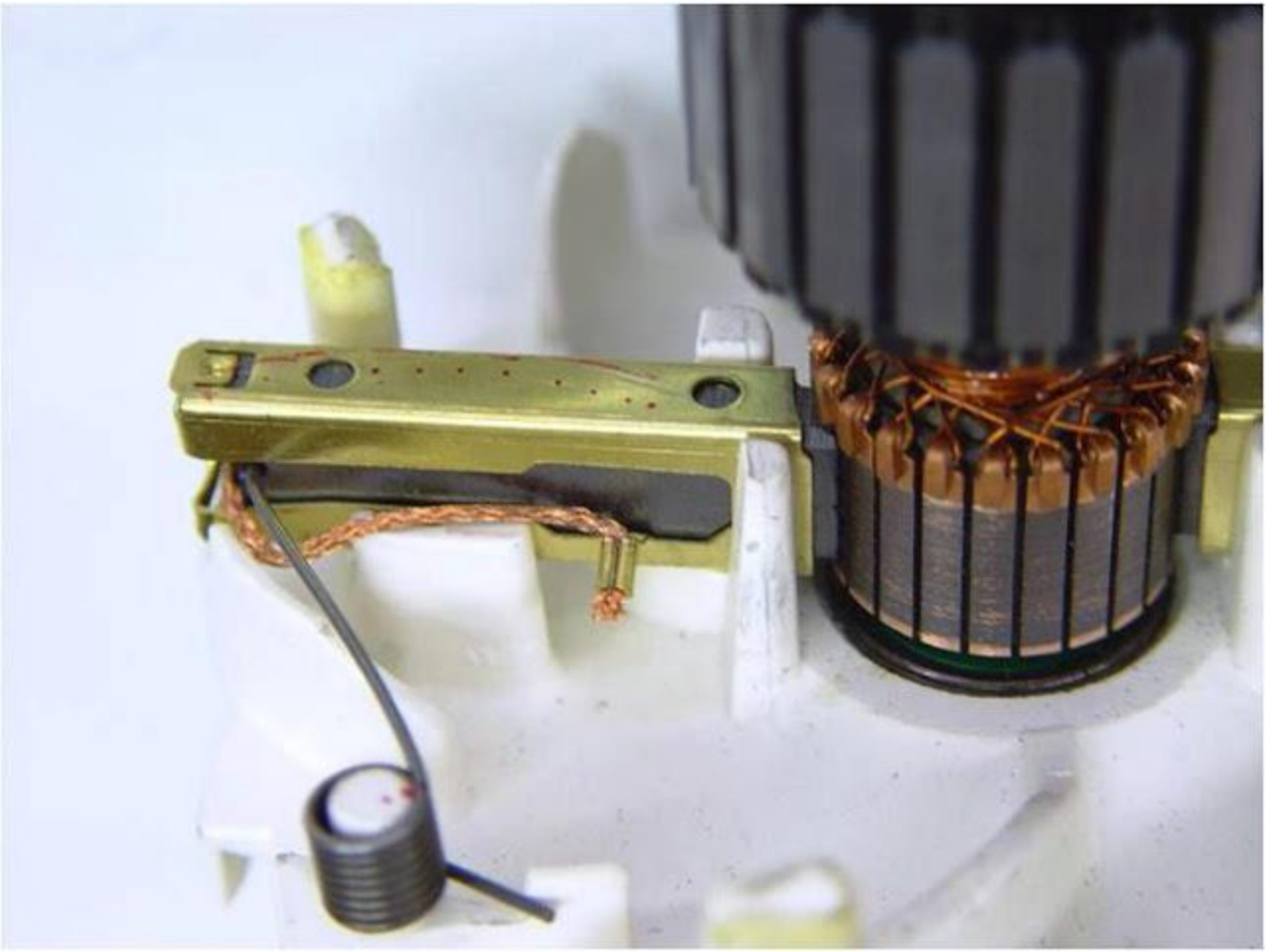
Brushed DC motor construction





http://www.electrical-knowhow.com/2012/05/classification-of-electric-motors.html

DC motor commutator



A!

DC motor field generation

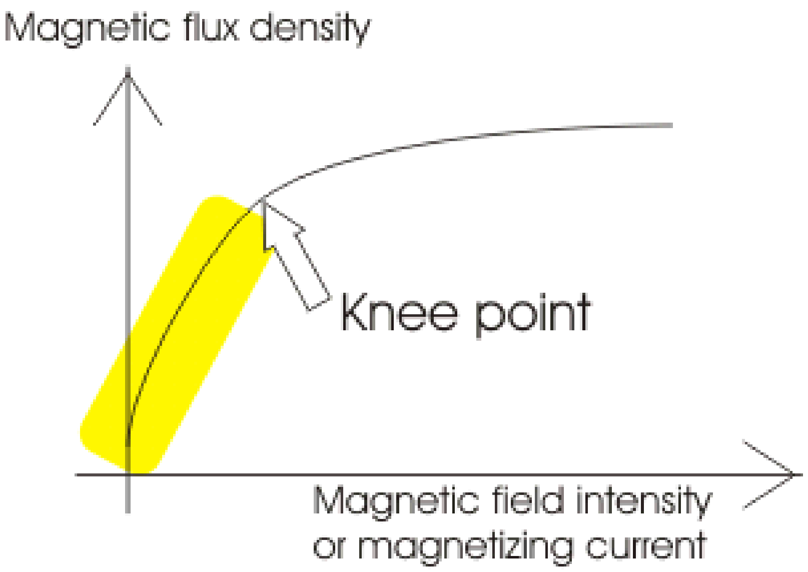
Permanent magnet

- Permanent magnet **stator** (Brushed)
- Permanent magnet **rotor** (Brushless Lecture 4)

Field coils (electromagnets)

- Separately excited
- Series or parallel wound

Material saturation
limits field magnitude



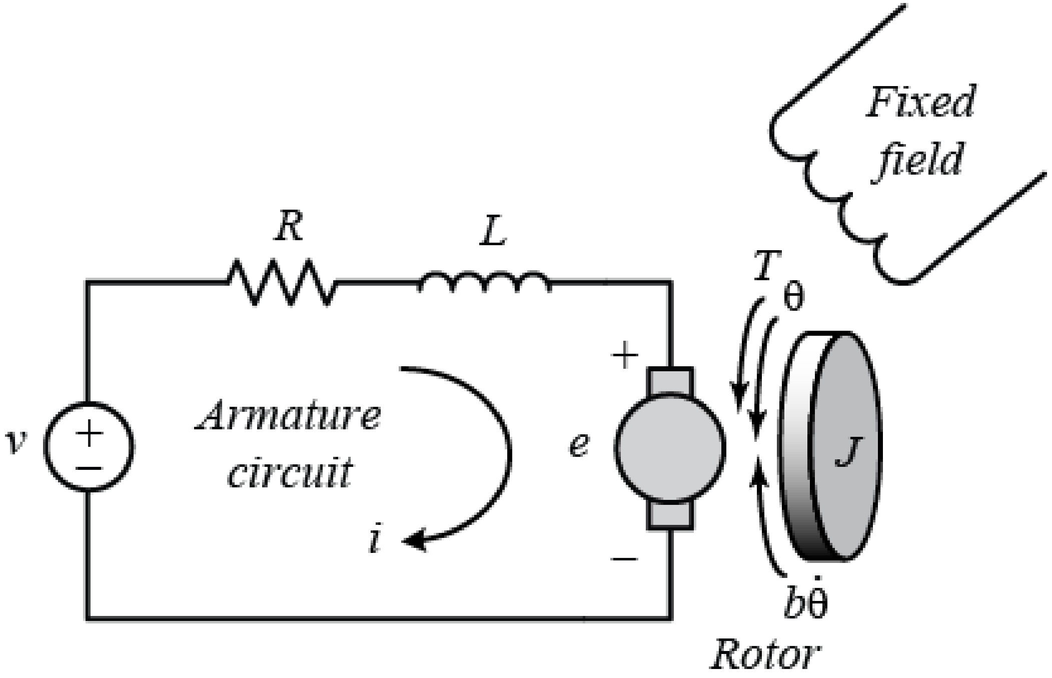
SIMPLE first order electrical modelling: equations

Input power	$P_{in} = UI$
Output power	$P_{out} = T\omega$
Resistive loss in windings	$P_{res} = RI^2$
Produced torque	$T = 2NrBlI = K_t I$
Back electromotive force	$V_{bemf} = 2NBlr\omega = K_e \omega$
Induced voltage across an inductor	$V = L\frac{dI}{dt}$

A!

Simple electrical model of a DC motor

Equivalent circuit



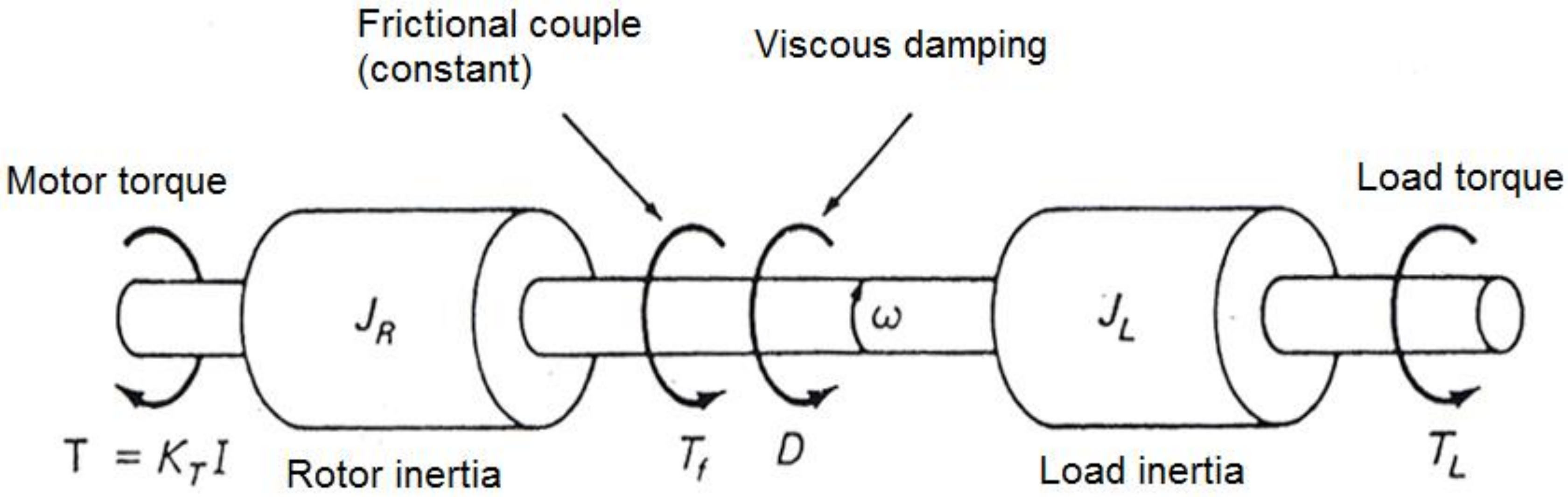
http://ctms.engin.umich.edu/CTMS/index.php?example=MotorSpeed&section=SystemModeling

Mathematical model

$$U = L_A \frac{dI}{dt} + R_A I + K_E \omega$$

Mechanical model of an electric motor

Physical model



Mathematical model

$$T = K_T I = (J_R + J_L)\frac{d\omega}{dt} + D\omega + T_f + T_L$$

Linear system would be: $\sum \mathbf{F} = m\frac{dv}{dt} + bv + F_1 + F_2$

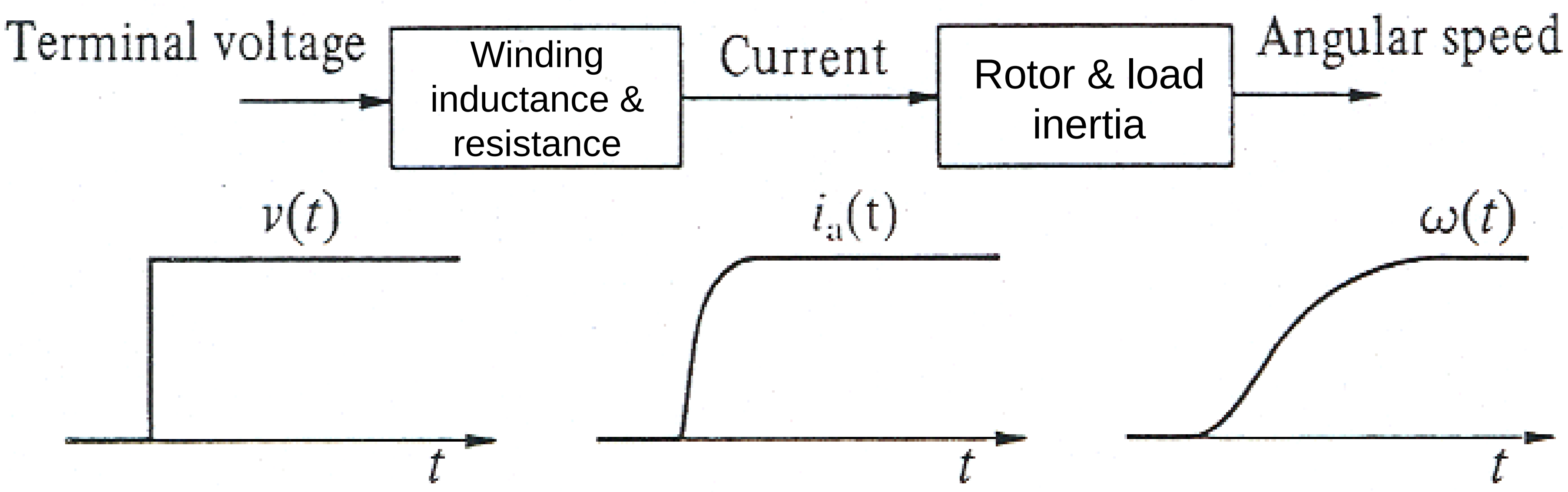
Combined mathematical model

System of two differential equations

Electrical part $U = L\frac{dI}{dt} + RI + K_e\omega$

Mechanical part $T = K_t I = J_{tot}\frac{d\omega}{dt} + D\omega + T_f + T_l$

Time constants of a motor



A!

Power losses

Resistive losses

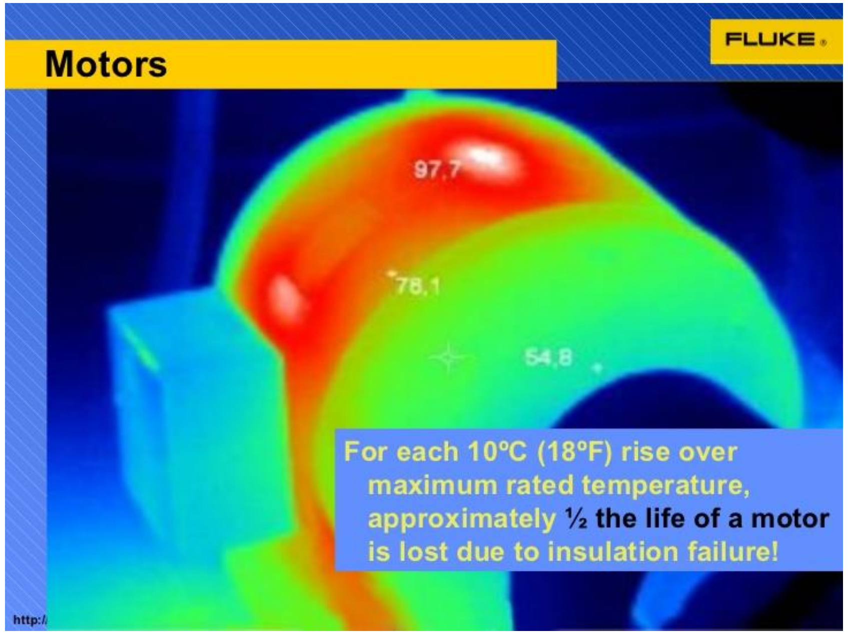
- Proportional to the square of the current $P = RI^2$ (and torque, because $T=K_tI$)
- Resistance depends on the temperature (resistance goes up 0.4%/K)

Core losses (altering magnetization)

- Proportional to the rotating speed

Mechanical losses

- Bearing friction
  - proportional to the rotating speed
- Damping (air etc.)
  - proportional to the square of rotating speed

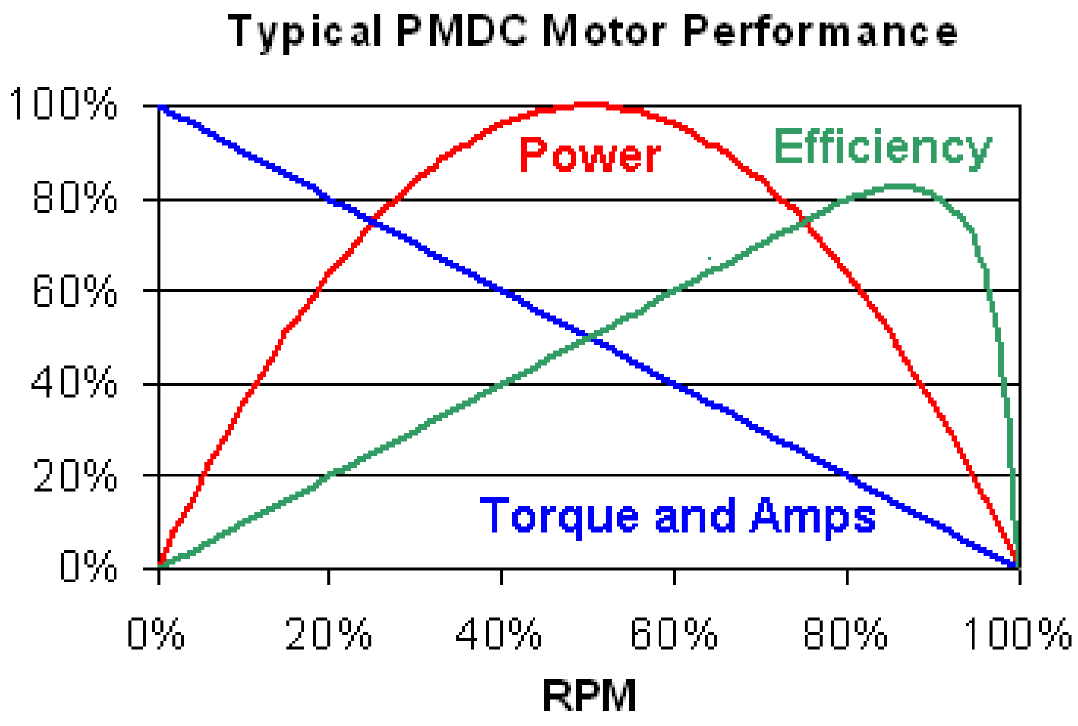


A!

Characteristics of a PMDC motor

PMDC = permanent magnet DC

Maximum torque and efficiency are speed dependent



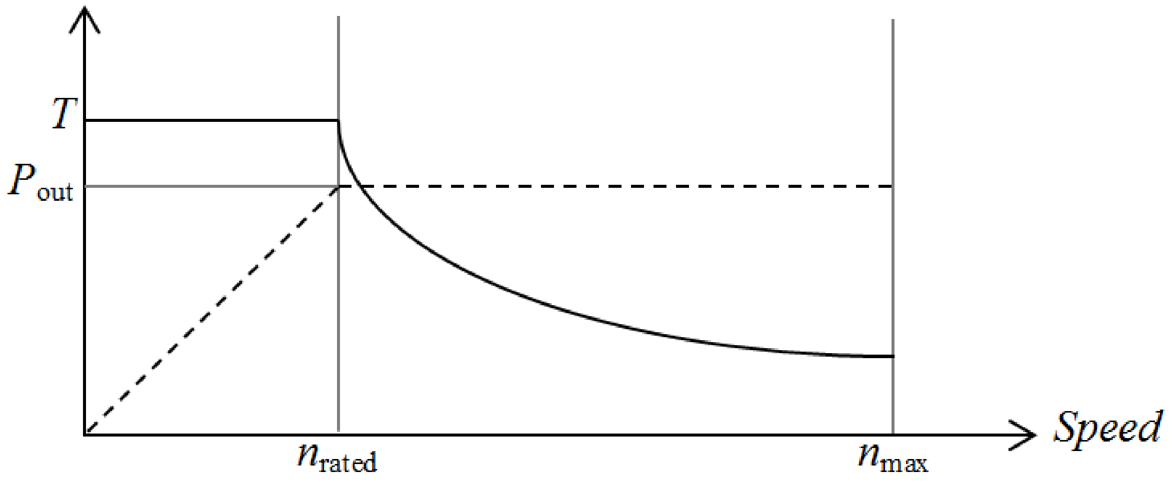
A!

Field weakening – if you have field coils

Reduce magnetic field flux density B

- Smaller B
  - Smaller torque constant $K_t \sim B$
  - Smaller BEMF constant $K_e \sim B$
- Smaller K_t -> less torque
- Smaller K_e -> more angular velocity

$$T = K_t I = 2NrBl \cdot I$$
$$V_{bemf} = K_e \omega = 2NBlr \cdot \omega$$



A!

Operating limits of a motor

Temperature

- Winding insulation melting temperature
- Permanent magnet demagnetization temperature

Voltage

- Winding insulation breakdown voltage

Mechanical strength & dynamics

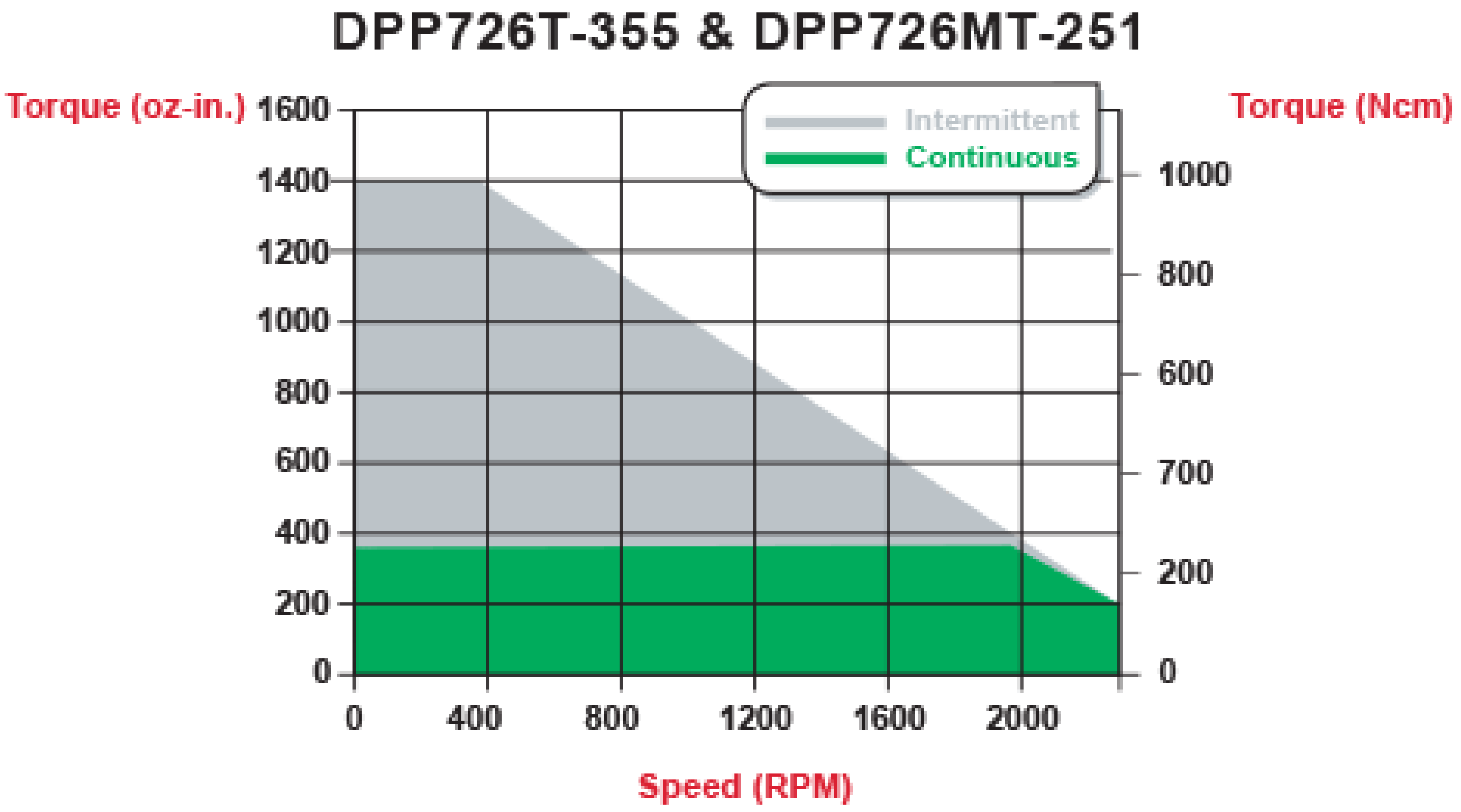
- Rotor breakdown speed, vibration, unbalance

Commutation speed

- Mechanical commutation has its limits
- Controller speed (Lecture 4)

A!

Operating limits of a PMDC motor



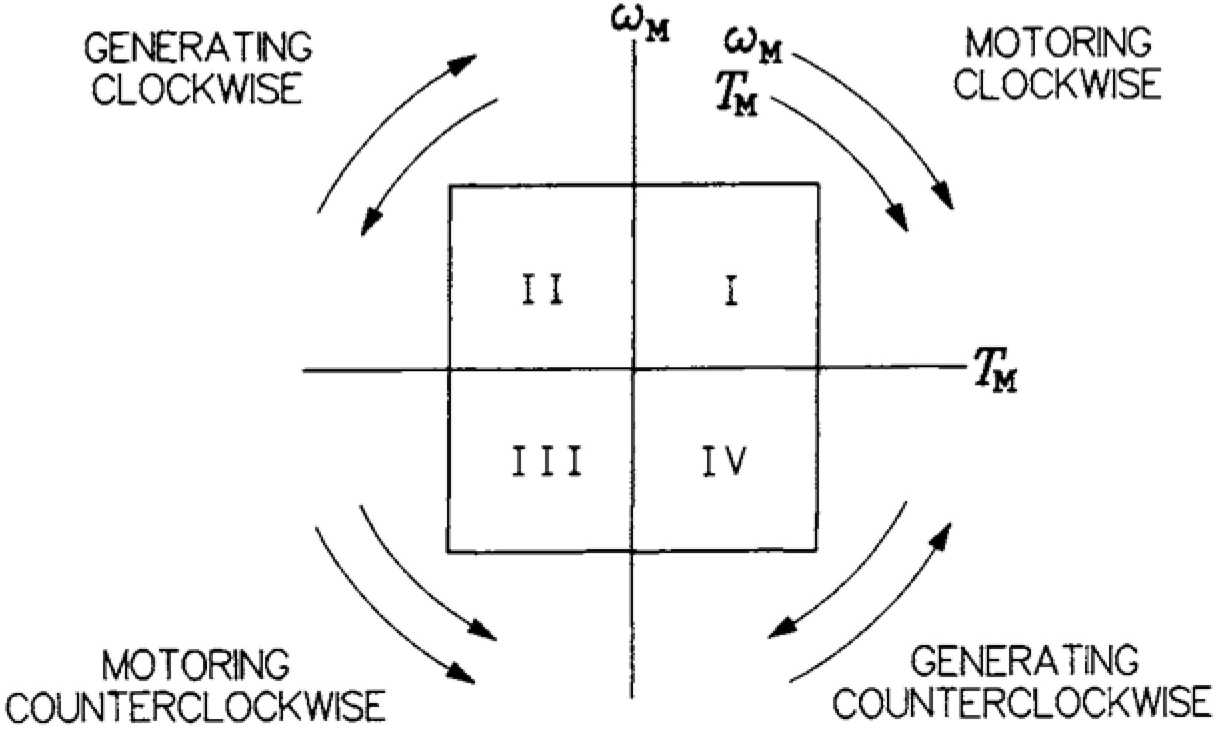
http://www.electrocraft.com/products/pmdc/DPP720/

Example of a brushed DC motor

https://www.maxonmotor.com/maxon/view/product/283866

Nominal voltage	48 V
No load speed	10100 rpm
No load current	16.2 mA
Nominal speed	9020 rpm
Nominal torque (max. continuous)	30.3 mNm
Nominal current (max. continuous	0.687 A
Stall torque	294 mNm
Stall current	6.5 A
Max. efficiency	90 %
Terminal resistance	7.39 Ω
Terminal inductance	0.746 mH
Torque constant	45.2 mNm/A
Speed constant	211 rpm/V
Mechanical time constant	3.2 ms
Rotor inertia	8.85 gcm^2
Thermal resistance housing-ambient	13.6 K/W
Thermal resistance winding-housing	4.57 K/W
Thermal time constant winding	21 s
Max. winding temperature	+125 °C
Bearing type	ball bearings
Max. axial load (dynamic)	2.5 N
Max. radial load	16 N, 5 mm from flange
Number of pole pairs	1
Number of commutator segments	9
Weight	95 g

Four quadrant operation: motor ~ generator



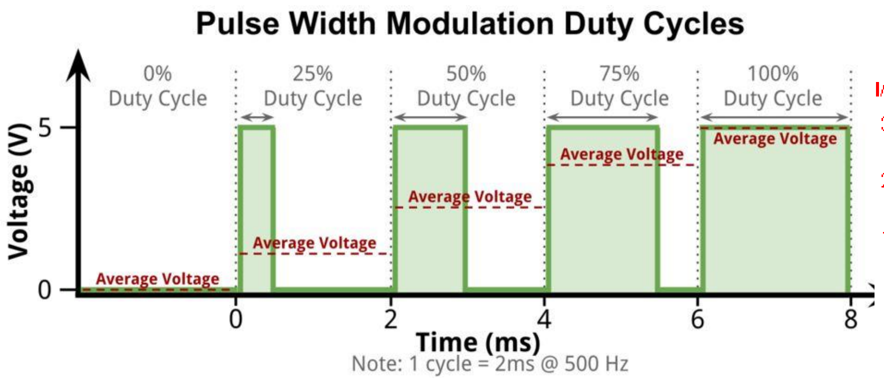
Brushed DC motor velocity control: PWM

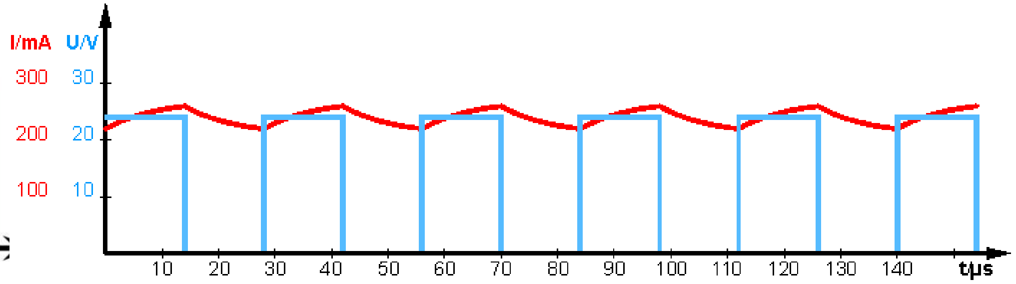
The torque is proportional to the current in the windings

$$T = K_T I = (J_R + J_L)\frac{d\omega}{dt} + D\omega + T_f + T_L \qquad U = L_A \frac{dI}{dt} + R_A I + K_E \omega$$

Current is controlled by voltage

- And voltage can be controller using pulse width modulation, PWM
- If the PWM frequency is high enough, the current stays almost constant (small fluctuations)





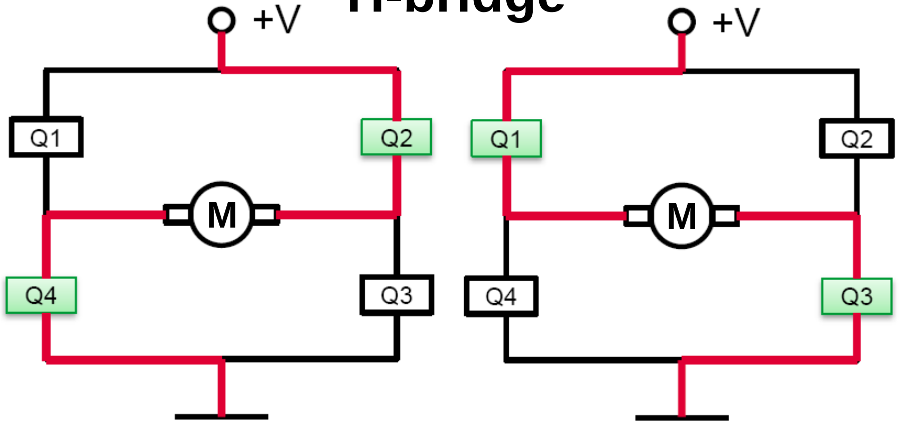
Brushed DC motor control

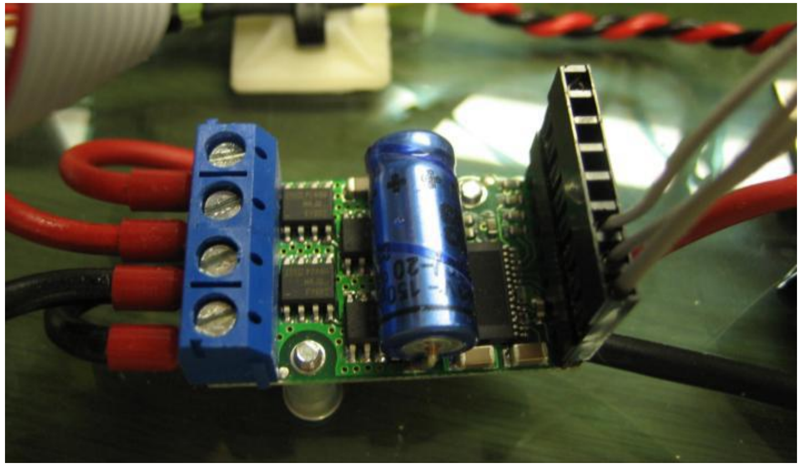
Motor needs large currents

- E.g. microcontroller signal not powerful enough for running the motor
- A separate motor drive circuit controls the motor current according to the microcontroller signal

One signal for PWM, one for direction

H-bridge





Why brushed DC motor

Cheap especially for low power (<1 kW) applications

- Simple voltage control, no variable frequency drive

Traditional

- Existing systems
- Known to any electrician

Full torque at low speed (as opposed to AC induction)

- Especially with series wound

Possibly smaller than AC induction

Why not

Brushes wear

- Maintenance up to several times a year in some applications

Sparking in brushes may cause electromagnetic interference

Aalto-yliopisto
Aalto-universitetet
Aalto University

Stepper motors

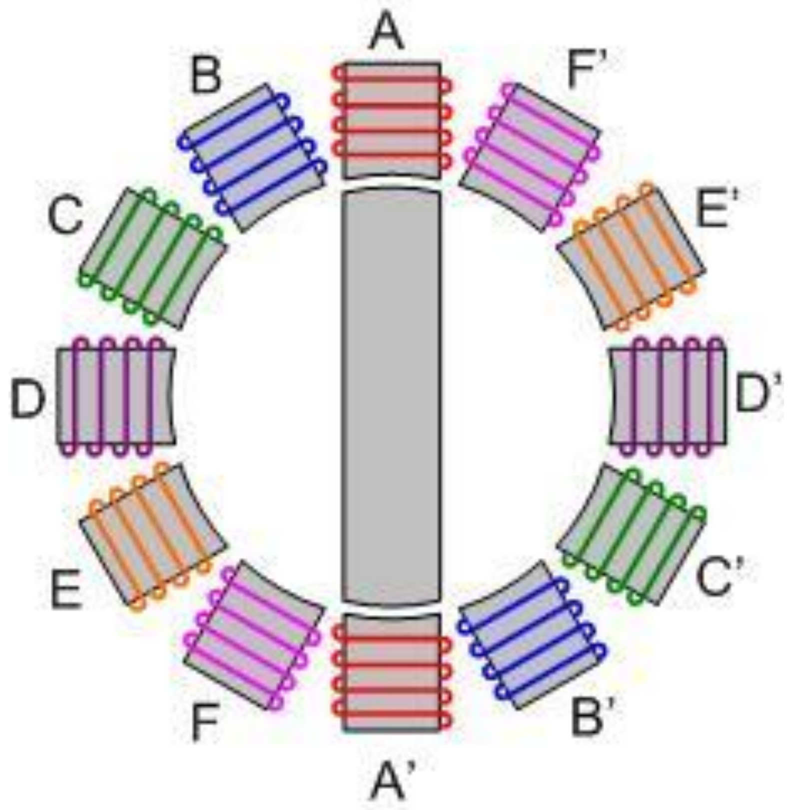
Stepper motors

Takes discrete steps

- Direction depends on
  coil energising order
- Step frequency determines speed
- Number of steps determines position

Maintains a position without active control

- Requires constant phase current



Stepper motors

Commonly 48 or 200 steps per revolution

- Corresponds to 7,5°or 1,8°per step

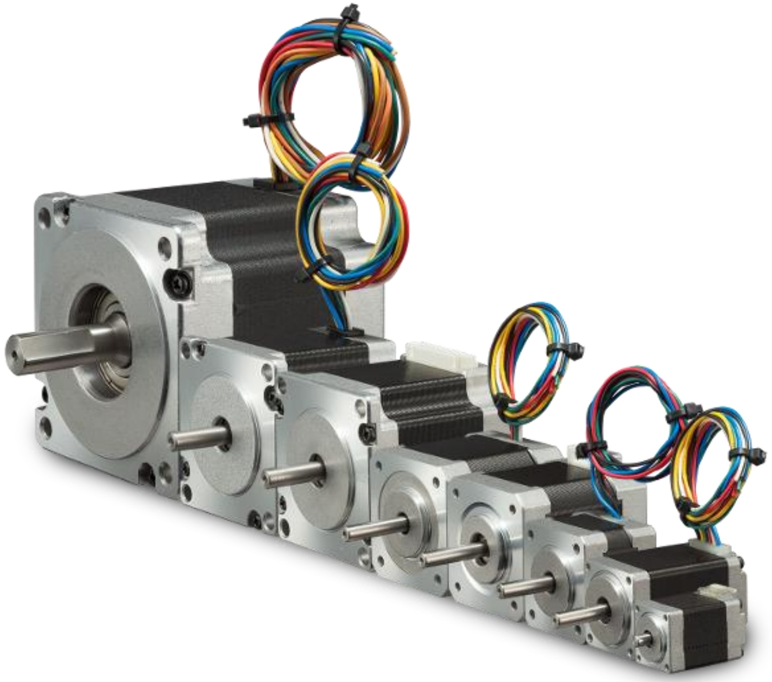
Usually low power (<750 W)

Low cost

NEMA sizes common

Three main types

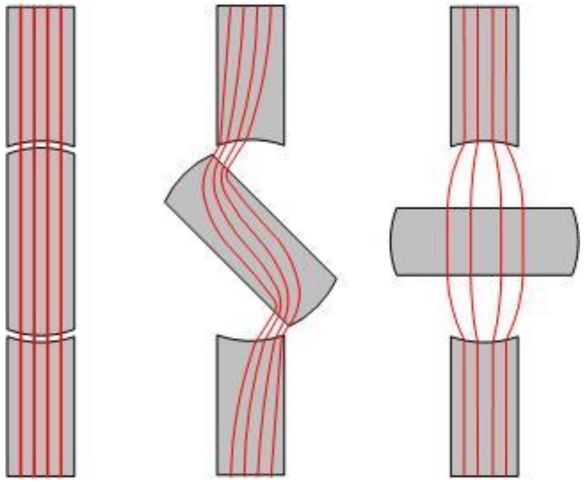
- Variable reluctance
- Permanent magnet
- Hybrid

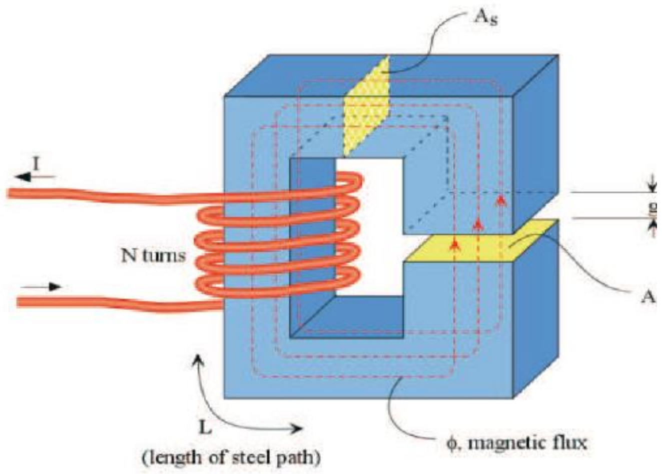


Generic principle of reluctance force motors

”Resistance” to magnetic flux

Reluctance force aligns objects to minimize reluctance





Not a stepper motor!

- Reluctance can be used also to produce continuous motion

Variable reluctance stepper motor

Cheap

Light rotor -> fast

Simpler control electronics

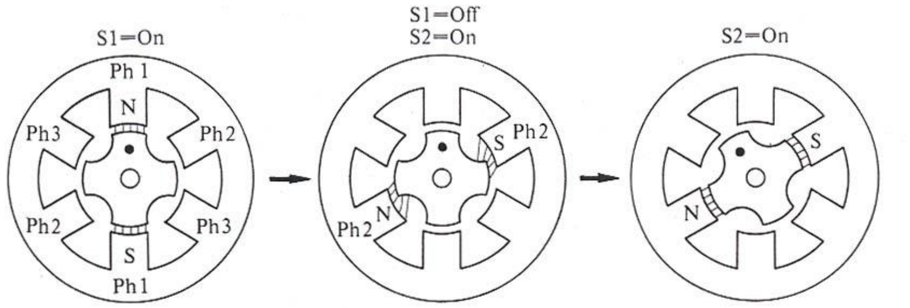
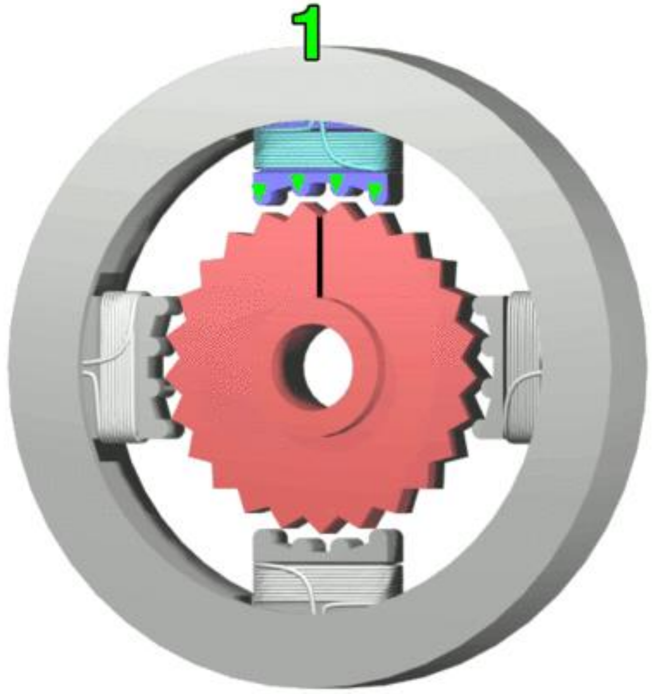


Fig. 2.12. How a step motion proceeds when excitation is switched from Ph1 to Ph2.

Kenjo, T., Stepping motors and their microprocessor controls

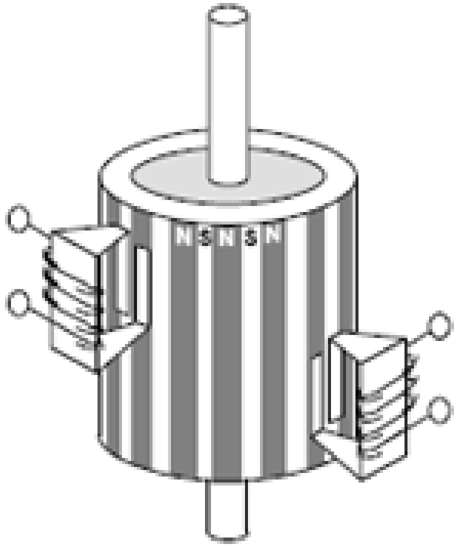


https://en.wikipedia.org/wiki/Stepper_motor

Permanent magnet stepper motor

Better torque

Worse resolution



http://www.robotiksistem.com/stepper_motor_types_properties.html

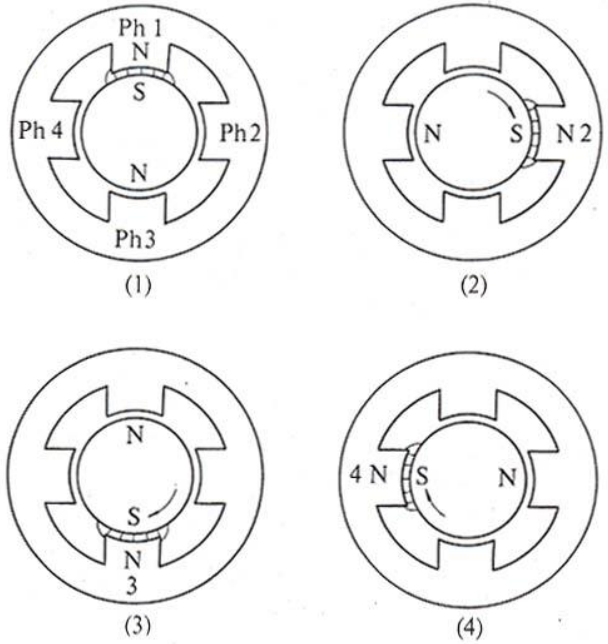


Fig. 2.29. Steps in a four-phase PM motor.

Kenjo, T., Stepping motors and their microprocessor controls

Holding torque

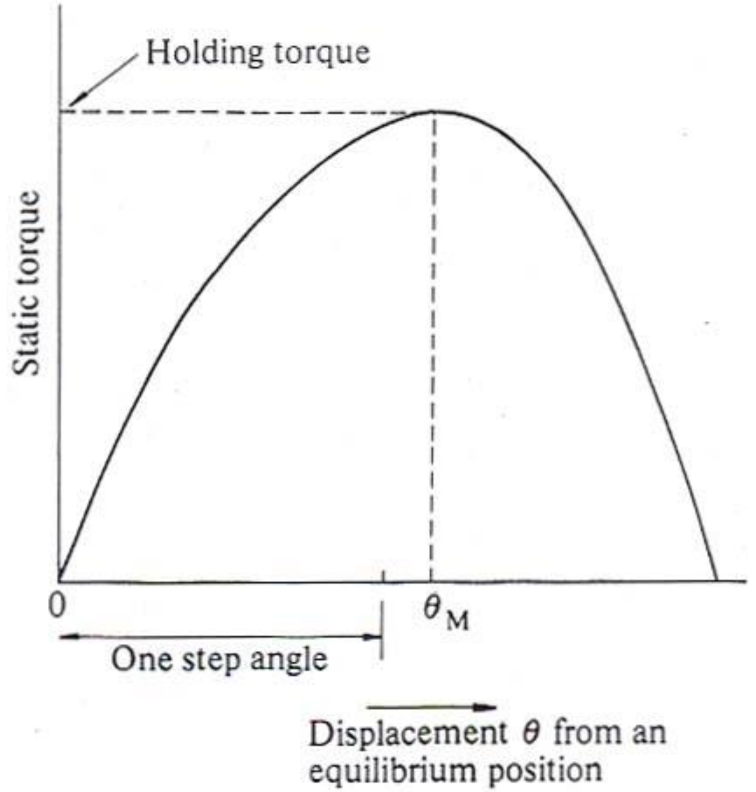
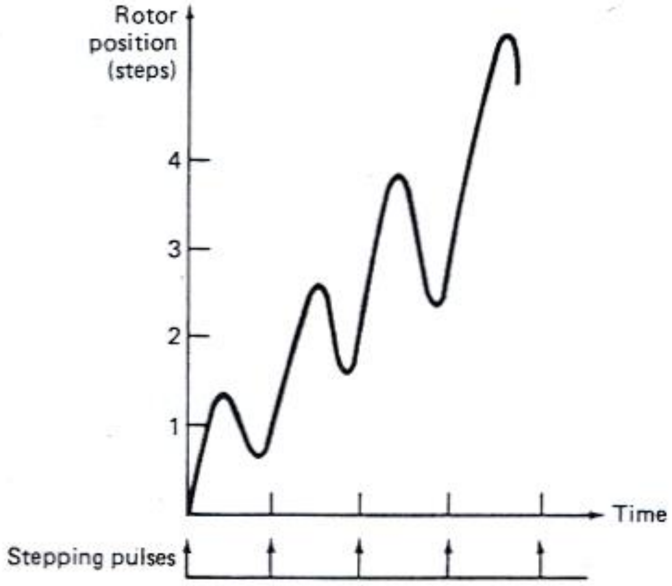


Fig. 2.73. T/θ characteristics.

Kenjo, T., Stepping motors and their micro-processor controls

Settling time



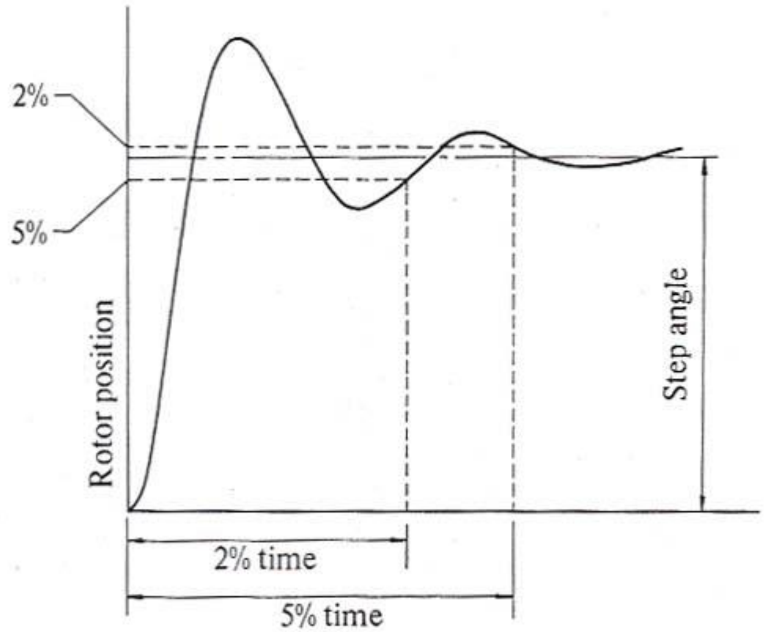
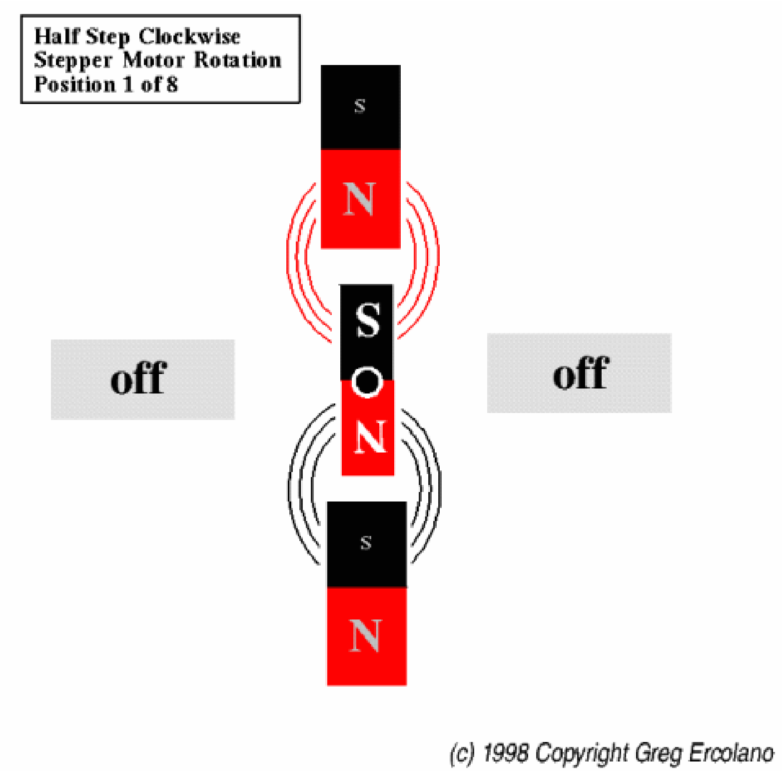


Fig. 4.6. Examples of settling time: the ordinary 5 per cent settling time and the 2 per cent one as a special case.

Kenjo, T., Stepping motors and their micro-processor controls

Half stepping

Doubles resolution



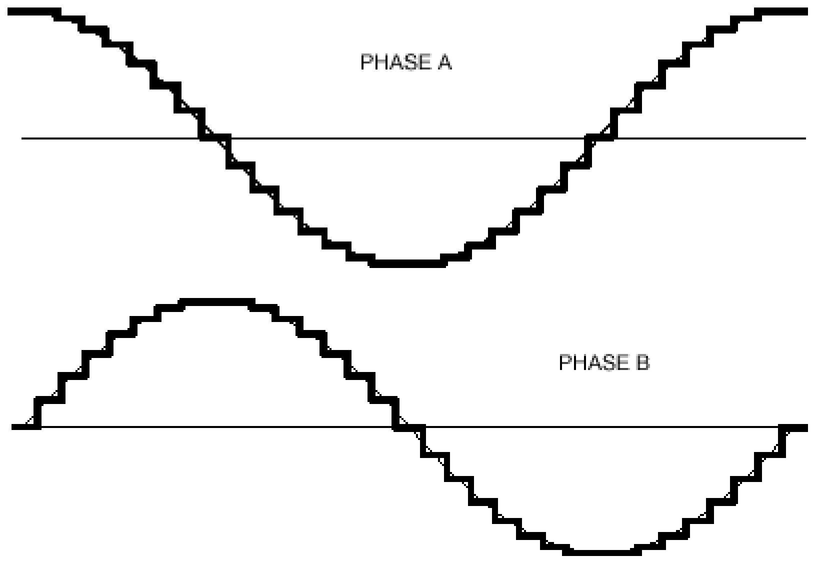
Micro stepping

More than two steps per full step

- over 10000 steps per revolution can be achieved

Resolution ≠ accuracy

- Smaller microsteps -> worse relative repeatability



http://forums.parallax.com/discussion/136024/doing-microstepping-with-the-propeller

Current control

Conflicting requirements

- High voltage recommended to overcome phase inductance
- Low voltage required to limit current and resistive losses

Solution: current control with variable voltage

Method: current measurement and PWM

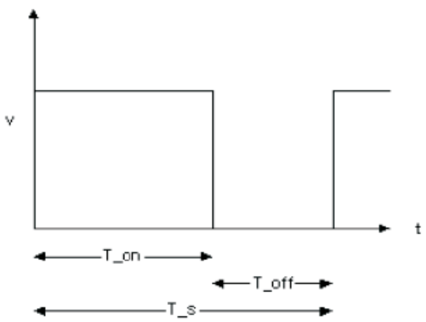


Fig. 11. Timing diagram of PWM.

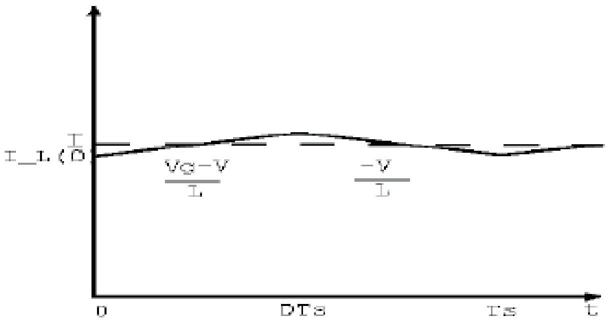
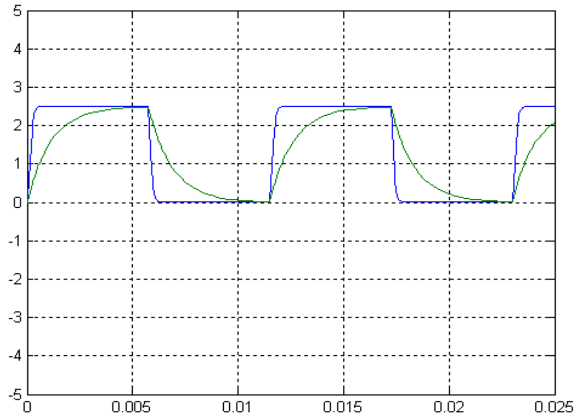


Fig. 12. Waveform of the current in constant state.



Stepper motor control example

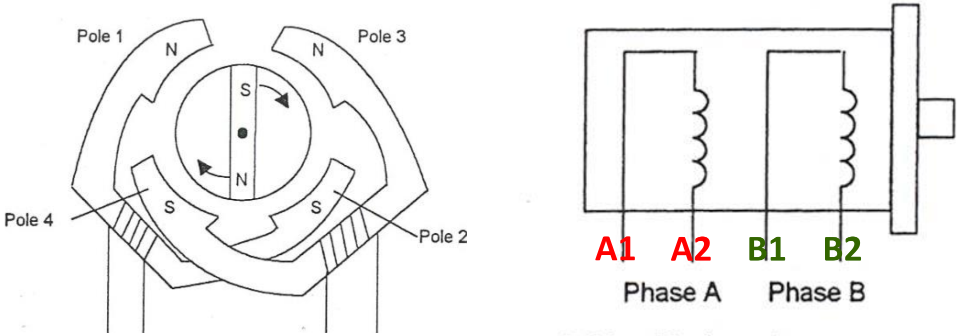


Fig. 7.44 Bipolar motor

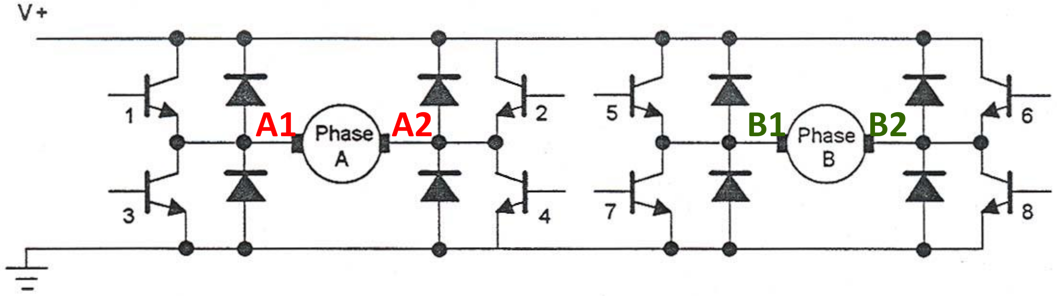


Fig. 7.45 H circuit

(Book: Bolton, Mechatronics)

Full stepping

Table 7.2 Switching sequence for full-stepping bipolar stepper

Step	Transistors			
	1 and 4	2 and 3	5 and 8	6 and 7
1	On	Off	On	Off
2	On	Off	Off	On
3	Off	On	Off	On
4	Off	On	On	Off

Half stepping

Table 7.3 Half-steps for bipolar stepper

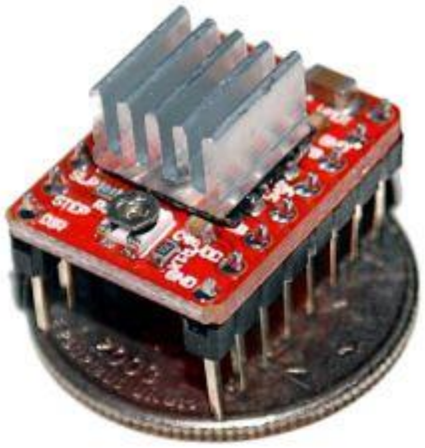
Step	Transistors			
	1 and 4	2 and 3	5 and 8	6 and 7
1	On	Off	On	Off
2	On	Off	Off	Off
3	On	Off	Off	On
4	Off	Off	Off	On
5	Off	On	Off	On
6	Off	On	Off	Off
7	Off	On	On	Off
8	Off	Off	On	Off

Lecture task

- Discuss in groups of 2 or 3 or 4 about stepper motor control (full stepping, half stepping, microstepping).
  - Make sure your colleague understands it – teach it!

- Make notes what was unclear – I will try to answer after the task.

Stepper motor drivers



Takes care of…

- Correct coil energising order
  - Commonly need just two signals: step and direction
- Half or microstepping
- Current control

Miniature drivers

- Phase current ~1 A
- Price starting from 5 €

Large drivers

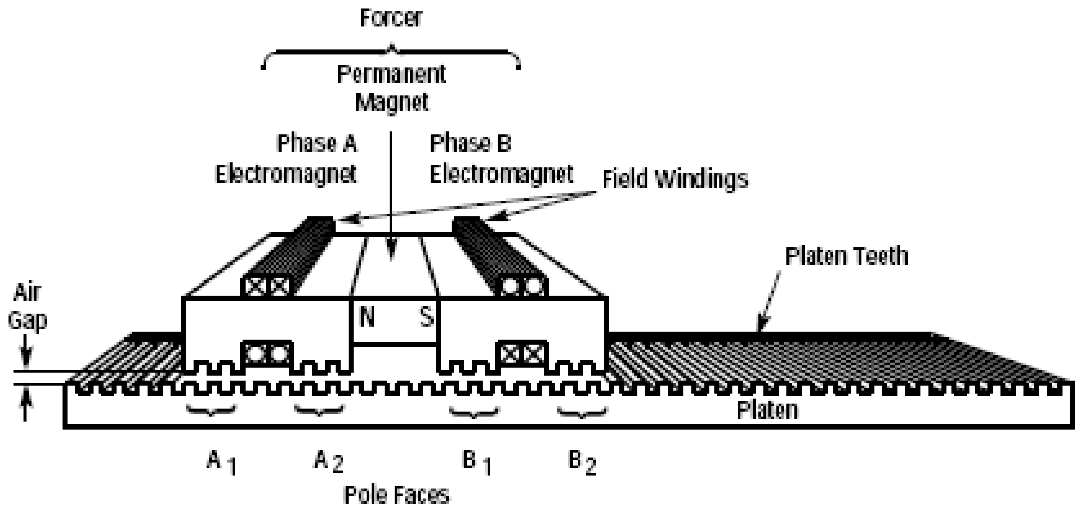
- Current 10+ A

XY table with steppers

Linear stepper

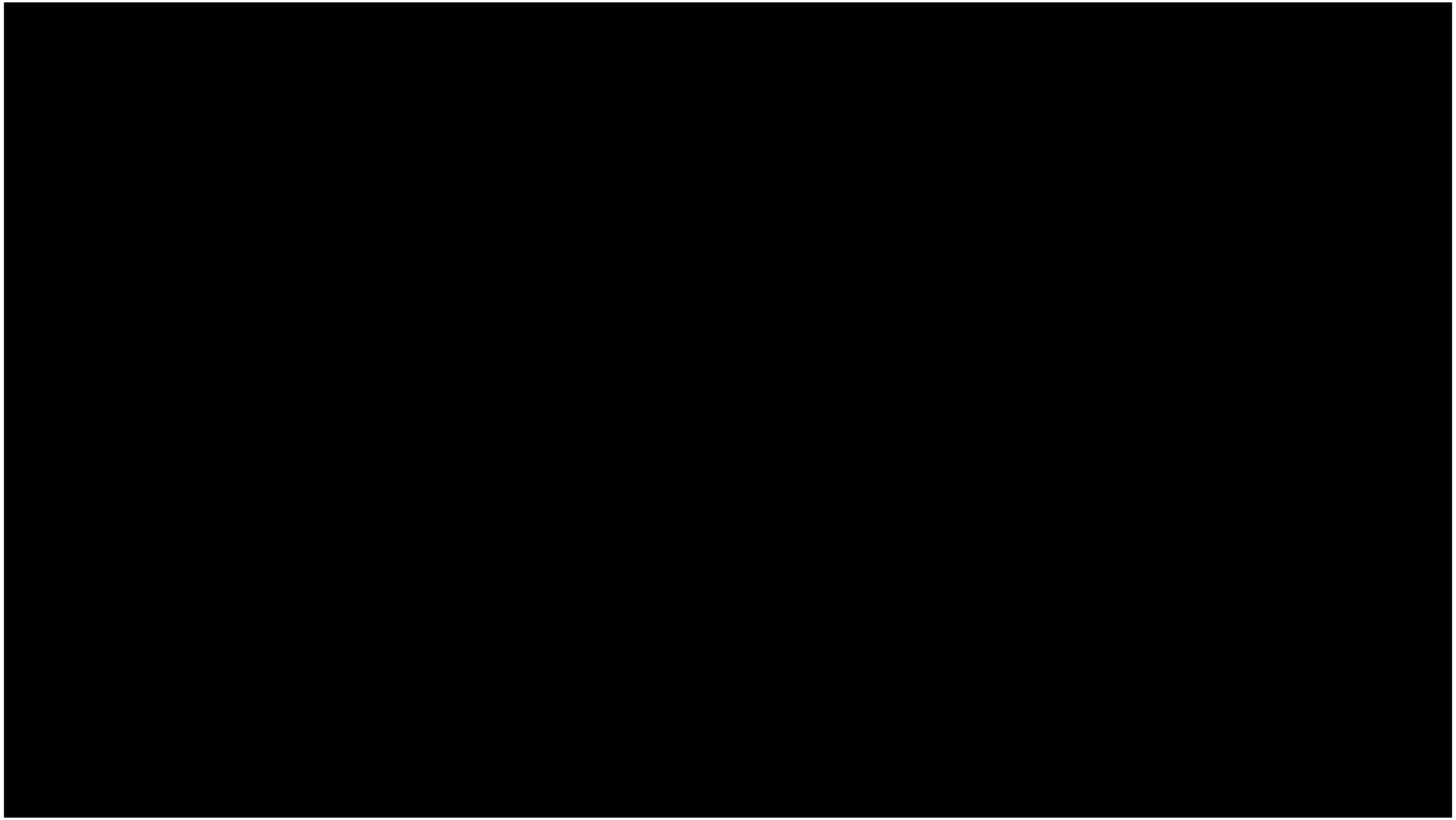
Functional principle similar to rotating versions

2D motion possible



A!

Dual axis linear stepper



Stepper summary

Fairly accurate positioning without position feedback

- Resolution from ~10 to 10000 steps per revolution
- Magnetic field acts as a spring
- Missed steps can be a problem

Stepper controller required

- Usually step and direction signals
- PWM current control recommended

Constant current consumption

- Usually low power applications

Feedback from last year, week 1

The assignments were fun to do. The provided materials were quite helpful to successfully complete the assignment.

I really don't get the idea of point reduction. This kind of model is demotivating, especially after a small misinput mistake.

I liked the exercises, they were not too challenging but not too easy. Fun and encouraging.

It would be nice to have the green dot visible when the task is submitted on the left of the exercise. It would help to see which of the exercises are done!

Very thorough and good. I liked the fact that both basics of mechanics and electrics were refreshed with exercises at the start of the course! good difficulty curve on the exercises

Exercises are interesting but really difficult