ME 327: Design and Control of Haptic Systems
Spring 2020

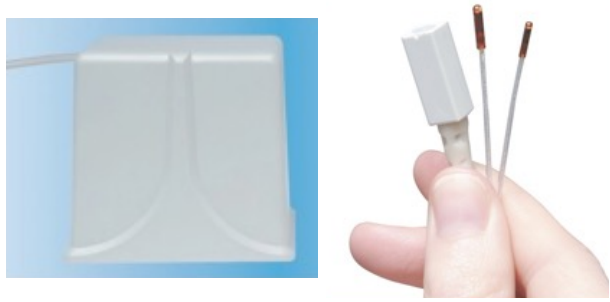
Lecture 8:
Kinesthetic haptic devices: sensors and actuators

Allison M. Okamura
Stanford University

sensors

sensing systems

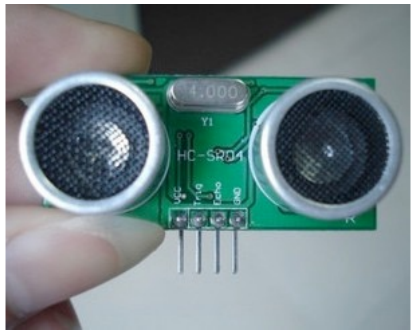
- magnetic
- optical
- acoustic
- inertial
- **mechanical**
  (our focus, since these are the sensors typically integrated with the actuator in kinesthetic haptic devices)



magnetic: TrakStar, Ascension

optical: Polaris, NDI

optical: Microsoft Kinect



acoustic: ultrasonic proximity sensor, BiF

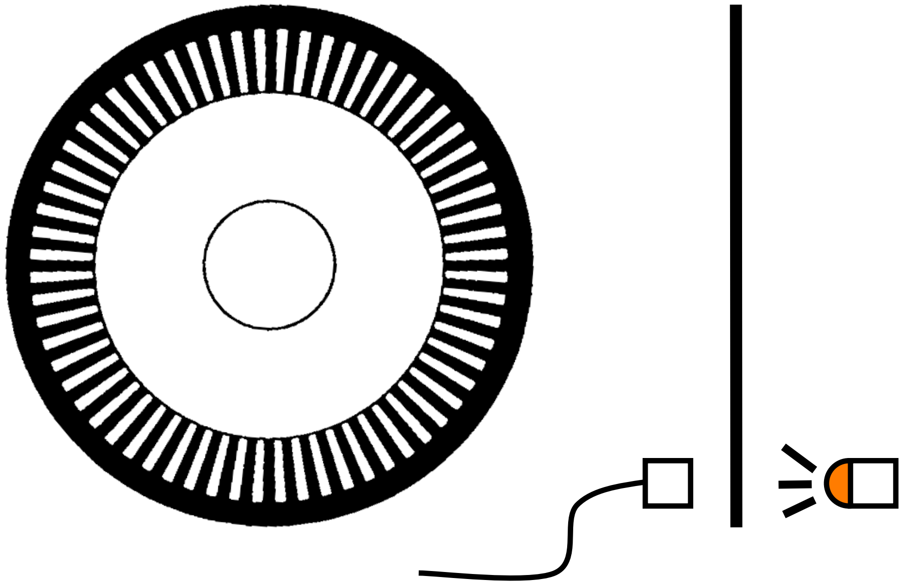
inertial: wearable IMU, MotionNode

mechanical: Faro arm

mechanical trackers

- ground-based linkages most commonly used
- joint position sensors
  - digital: optical encoders are most common
  - analog: magnetic sensors and potentiometers are most common

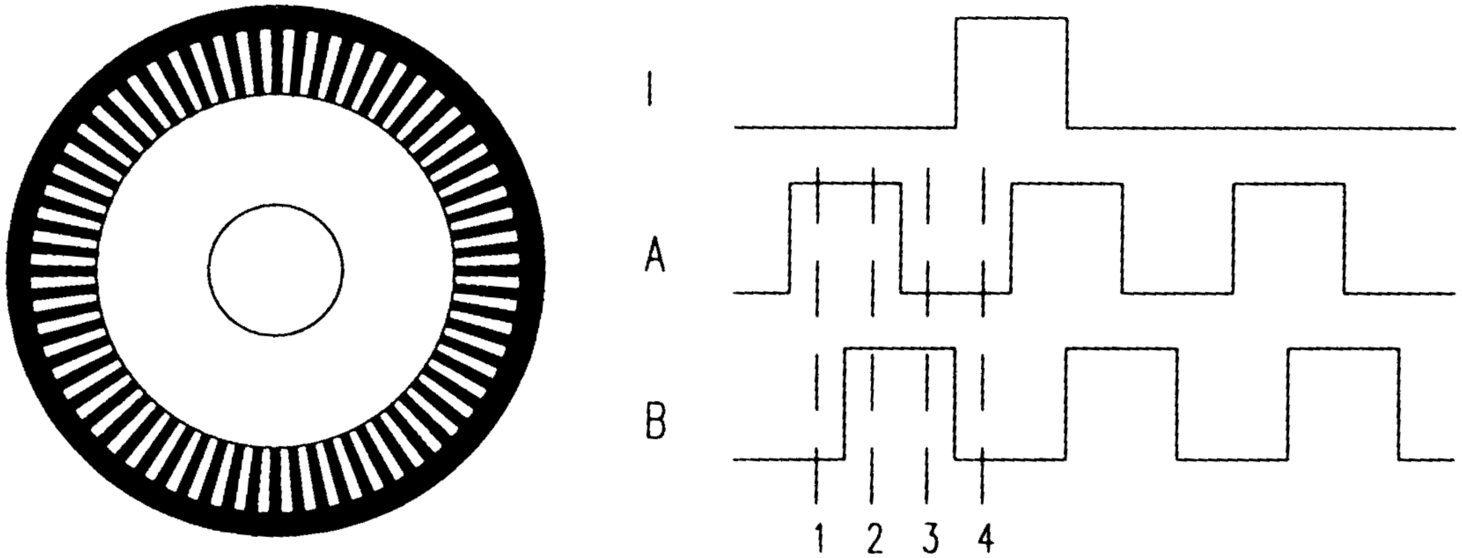
optical encoders

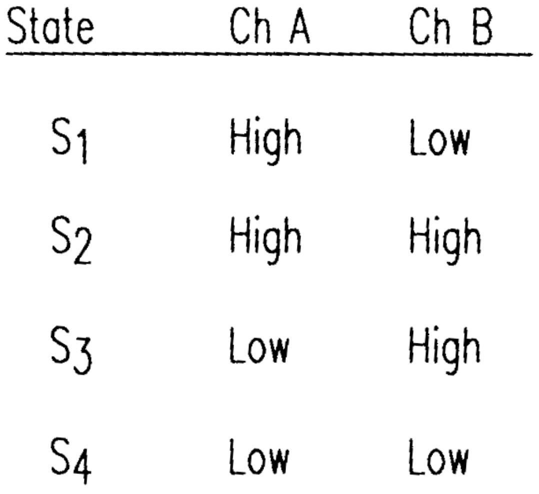


- how do they work?
  - A focused beam of light aimed at a matched photodetector is interrupted periodically by a coded pattern on a disk
  - Produces a number of pulses per revolution (Lots of pulses = high cost)
- quantization problems at low speeds
- absolute vs. referential

optical encoders

- phase-quadrature encoder

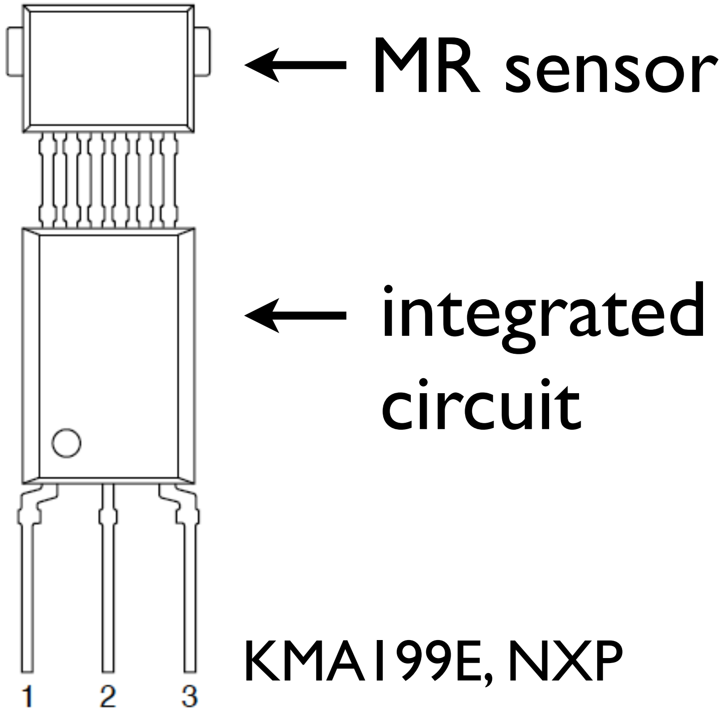




State	Ch A	Ch B
S_1	High	Low
S_2	High	High
S_3	Low	High
S_4	Low	Low

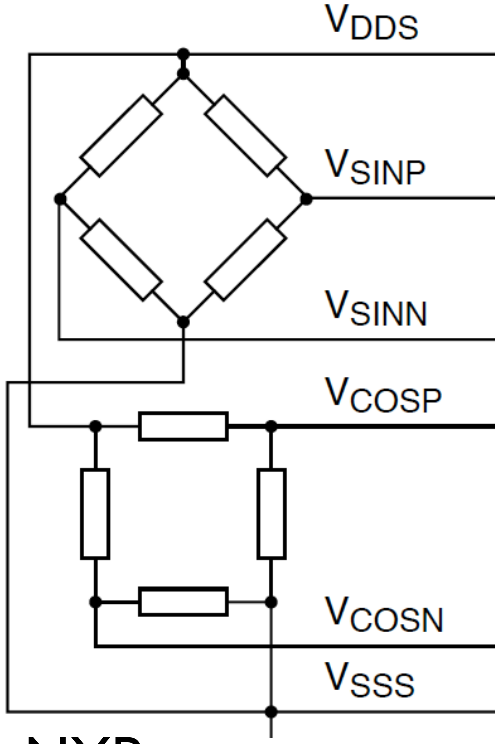
- 2 channels, 90° out of phase
  - allows sensing of direction of rotation
  - 4-fold increase in resolution

magnetoresistive angle sensors



KMA199E, NXP

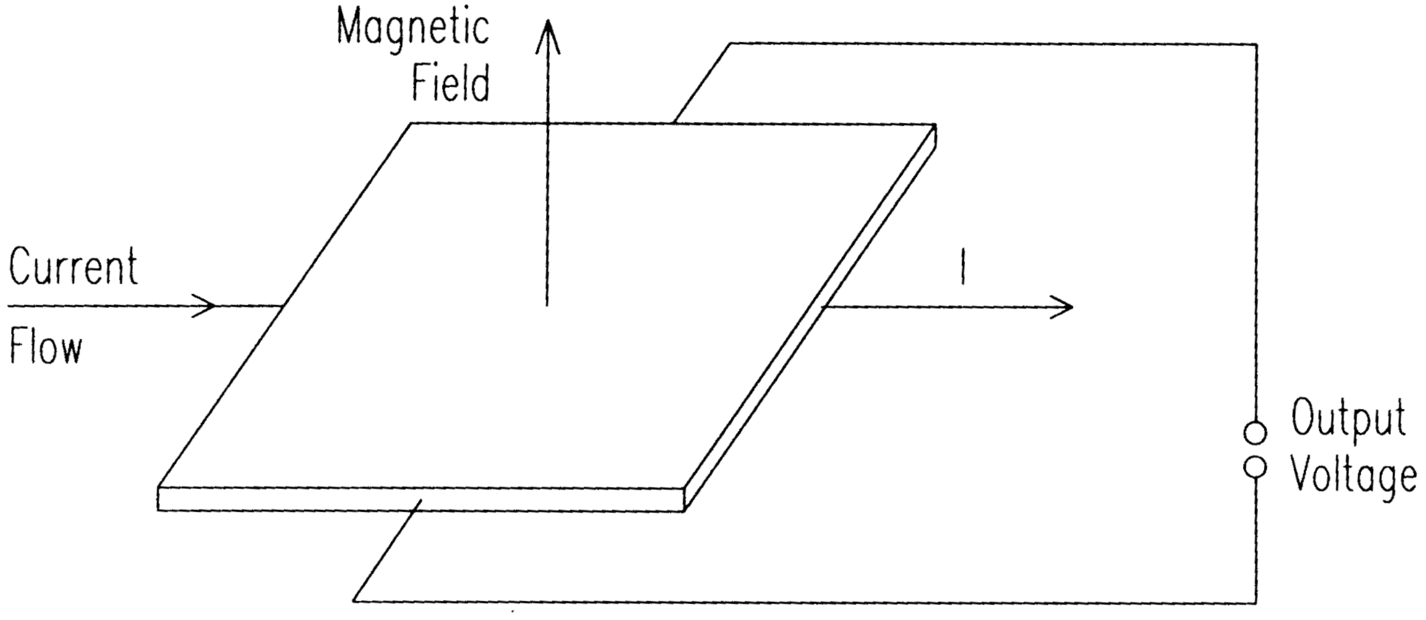
- magnetoresistive materials change their electrical resistance when an external magnetic field is applied
- the resistance depends on the angle between the magnetization vector of the ferromagnetic material and the direction of current flow (resistance is largest if they are parallel)
- often 4 sensors are connected in a Wheatstone bridge configuration (similar to strain gages)



KMA199E, NXP

Hall-Effect Sensors

a small transverse voltage is generated across a current-carrying conductor in the presence of a magnetic field



(Discovery made in 1879, but not useful until the advent of semiconductor technology.)

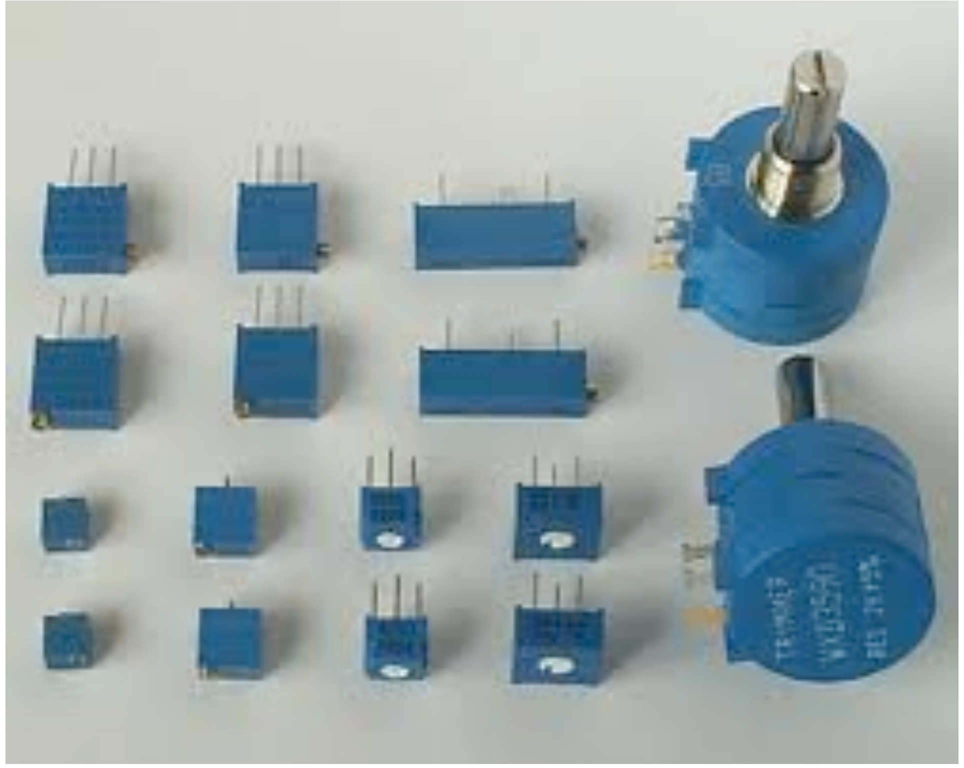
Hall-Effect Sensors

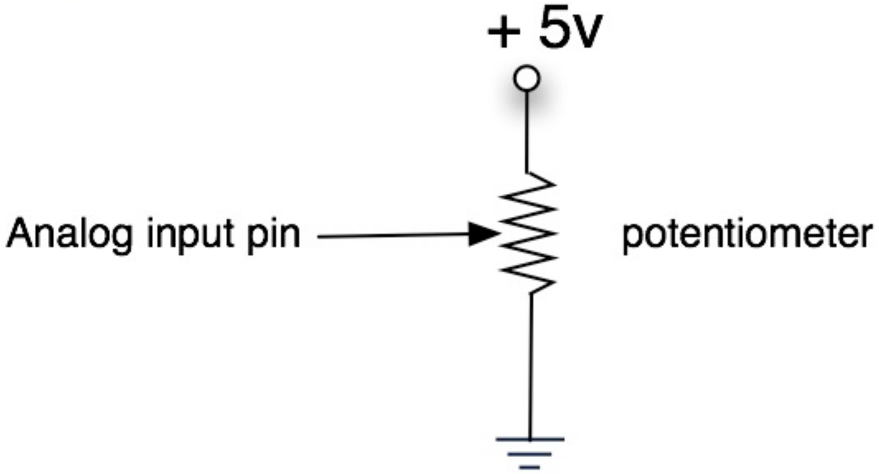
$$V_h = \frac{R_h I B}{t}$$

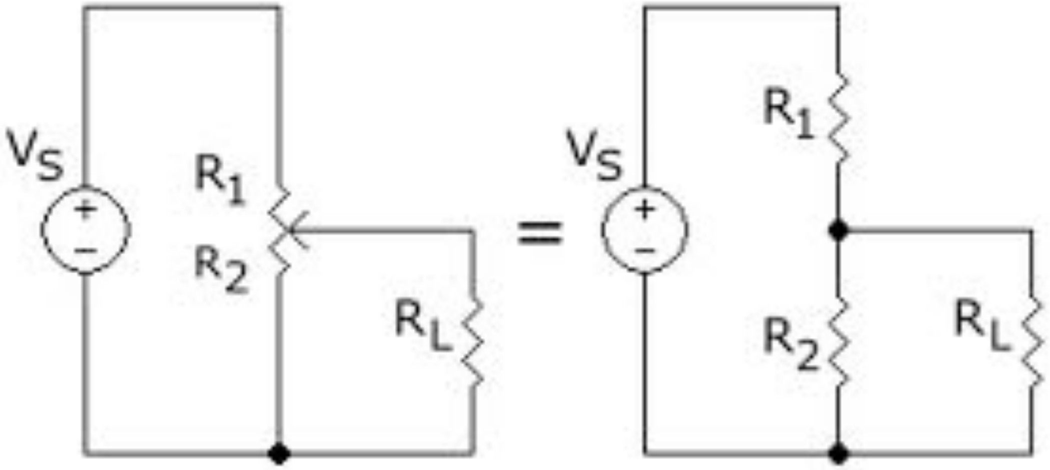
V_h = Hall voltage
R_h = Hall coefficient
I = Current
B = Magnetic flux density
t = Element thickness

- amount of voltage output related to the strength of magnetic field passing through.
- linear over small range of motion (need to be calibrated)
- affected by temperature, other magnetic objects in the environments

potentiometers

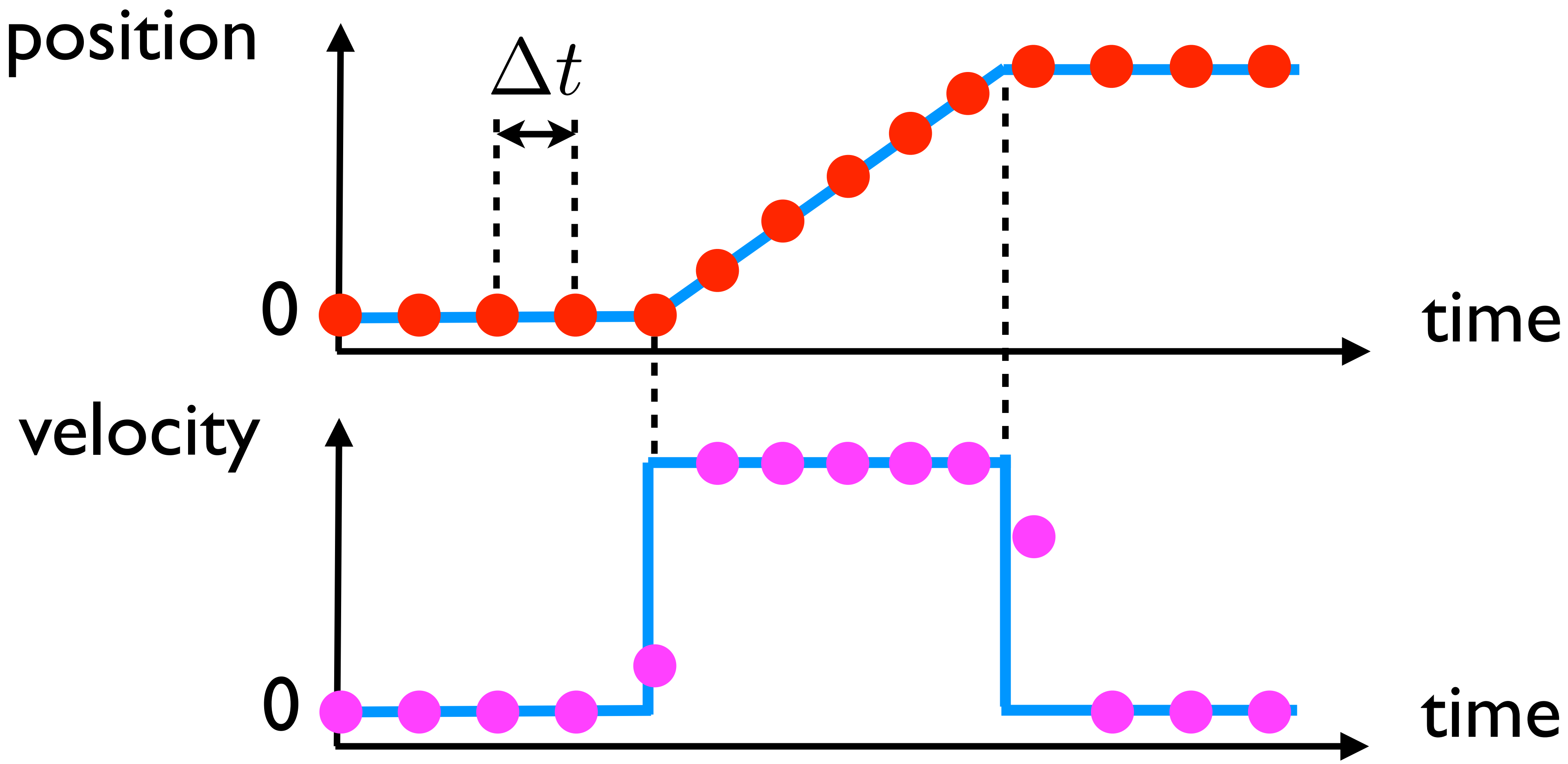






position, velocity, and acceleration

For the Hapkit, you can access position and time data from your Hapkit board



$$v_{\text{inst}} = \frac{dx}{dt} = \dot{x}$$

$$v_{\text{avg}} = \frac{\Delta x}{\Delta t}$$

acceleration is usually too noisy

measuring velocity

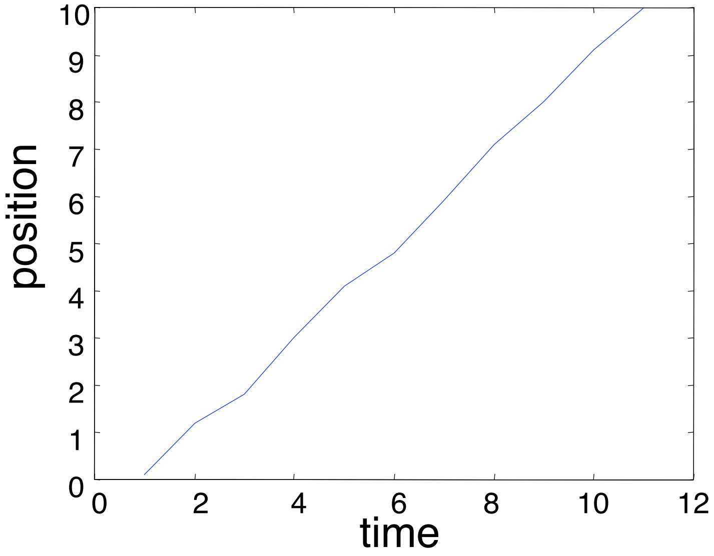
- differentiate position
  - advantage: use same sensor as position sensor
  - disadvantage: get noisy signal
- alternative
  - for encoders, measure time between ticks

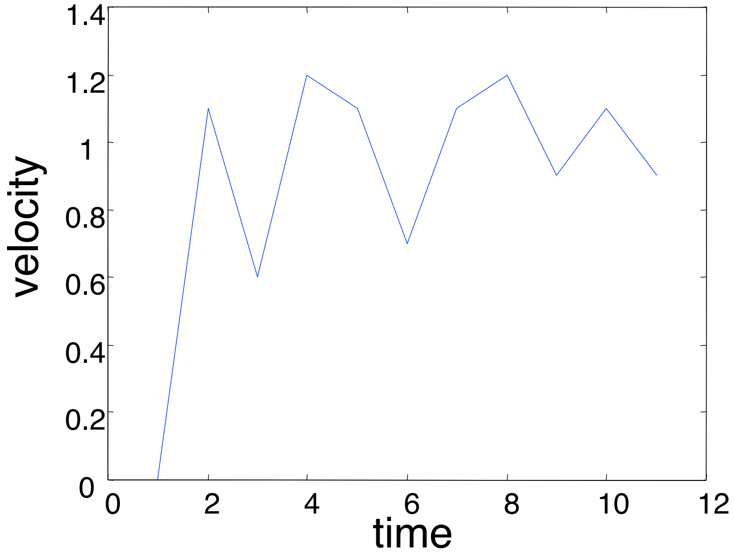
discrete differentiation

- many different methods
- simple example:
  - average 20 readings = P1
  - average next 20 readings = P2
  - where t is the the period of the servo loop

$$V = \frac{P1 - P2}{t}$$

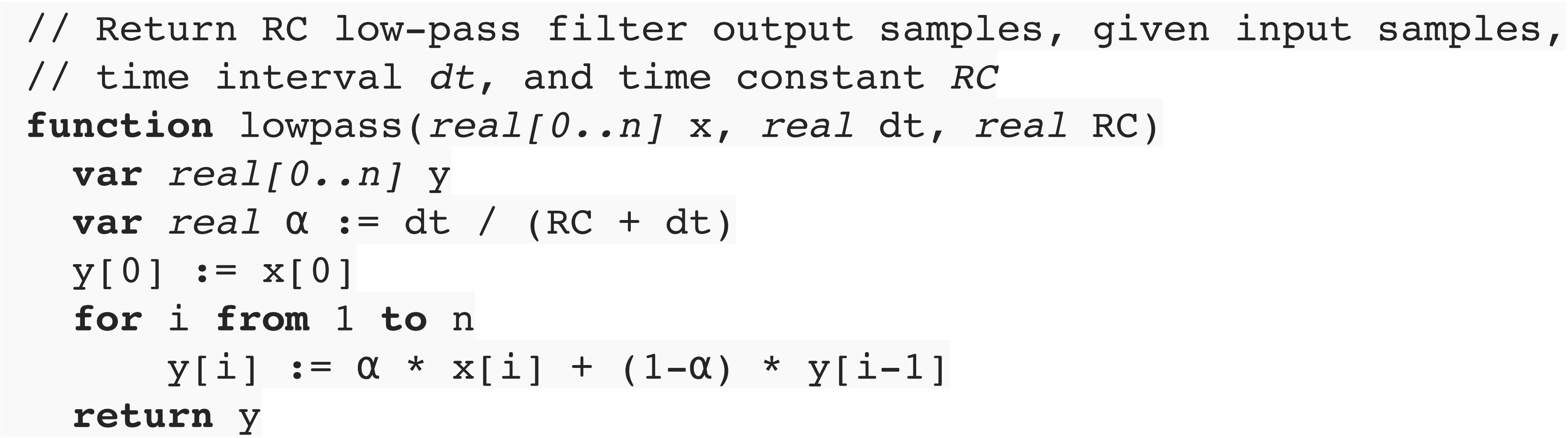
- differentiation increases noise
- usually need to filter





position/velocity filtering

- one example is the simple infinite impulse response (IIR) filter



```
// Return RC low-pass filter output samples, given input samples,
// time interval dt, and time constant RC
function lowpass(real[0..n] x, real dt, real RC)
  var real[0..n] y
  var real α := dt / (RC + dt)
  y[0] := x[0]
  for i from 1 to n
      y[i] := α * x[i] + (1-α) * y[i-1]
  return y
```

- pseudocode for real-time filtering:

```
new_value = read_from_sensor()
filtered_value = a*new_value + (1-a)*old_value
old_value = filtered_value
```

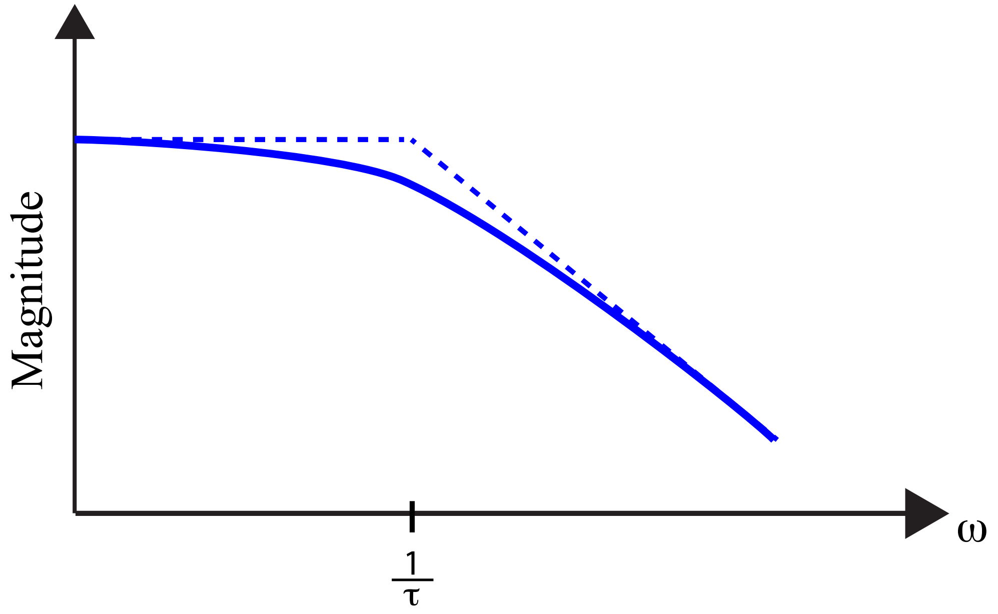
IIR filter

single-pole infinite impulse response (IIR) low-pass filter,
also called an exponential moving average filter

$$H = \frac{1}{\tau s + 1}$$

τ is defined as one divided by the cutoff frequency, i.e. $\tau = \dfrac{1}{\omega_c}$

You choose the cutoff frequency to be the frequency at which the amplitude of the response begins to roll off.



IIR filter

implementing in the (discrete) time domain:
compute a weighting parameter α that determines the relative weight of old versus new measurements.

$$\alpha = \frac{\Delta T}{\tau}$$

time between samples of our discrete system

calculated based on desired cutoff frequency

The larger alpha is, the more heavily it weights new information.

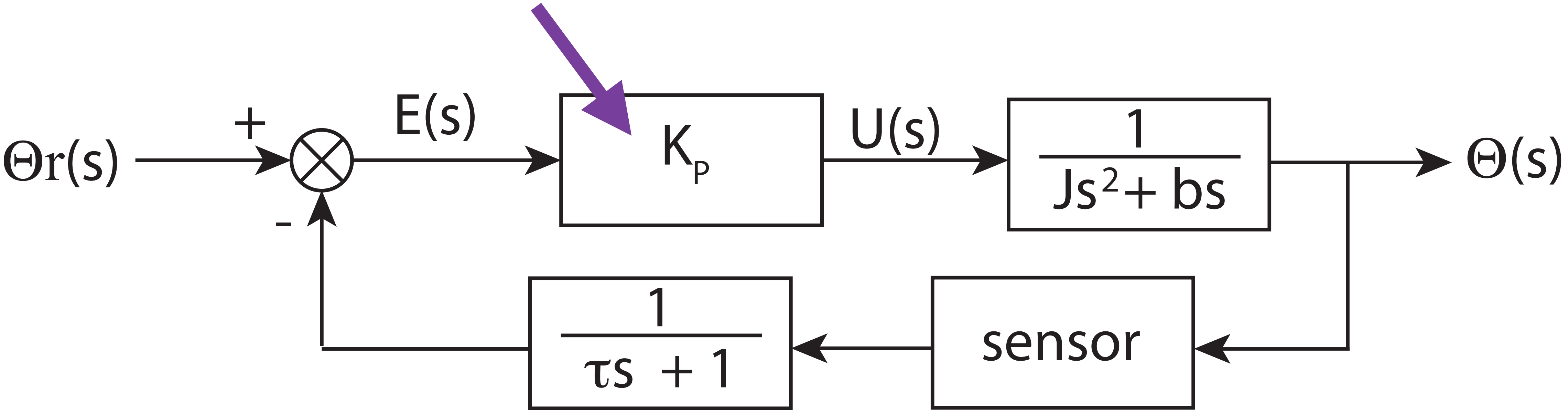
IIR filter

The filter runs in a loop, such that new measurements are acquired in each time step, and the old measurement will be saved from the previous loop

$$\theta_{updated} = \alpha\theta_{new} + (1 - \alpha)\theta_{old}$$

$$\theta_{old} = \theta_{updated}$$

In the case of a virtual spring with stiffness K_p and center at θ_r



IIR filter derivation

$$H = \frac{1}{\tau s + 1} = \frac{\Theta_{old}}{\Theta_{new}}$$
$$\Theta_{new} = (\tau s + 1)\Theta_{old}$$

Take the inverse Laplace transform…

$$\tau \frac{d\theta_{old}}{dt} + \theta_{old} = \theta_{new}$$

Convert from continuous time to discrete time with timestep ΔT…

$$\tau \frac{\Delta\theta_{old}}{\Delta T} + \theta_{old} = \theta_{new}$$

$$\Delta\theta_{old} = \theta_{updated} - \theta_{old} = \frac{\Delta T}{\tau}(\theta_{new} - \theta_{old})$$
$$\theta_{updated} = \theta_{old} + \frac{\Delta T}{\tau}(\theta_{new} - \theta_{old})$$
$$\theta_{updated} = \frac{\Delta T}{\tau}\theta_{new} + \left(1 - \frac{\Delta T}{\tau}\right)\theta_{old}$$
$$\theta_{updated} = \alpha\theta_{new} + (1 - \alpha)\theta_{old}$$

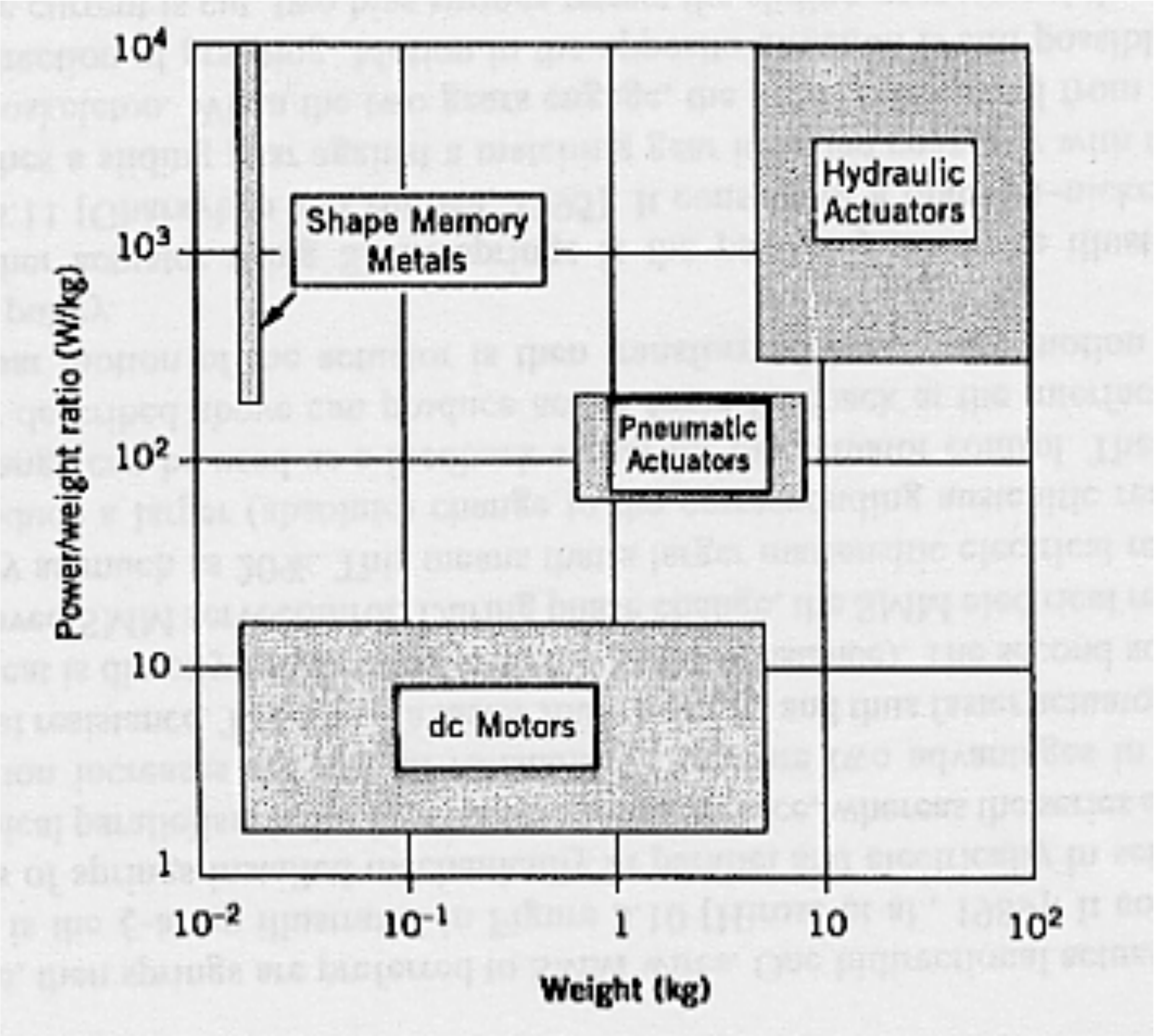
time-between-ticks

- encoders fare poorly at slow velocities
  - there may be very few ticks during a single servo loop
- instead, some specialized data acquisition boards use a special chip that measures time between ticks
  - fares poorly at high velocities

$$v = \frac{\Delta p}{\Delta t}$$

actuators

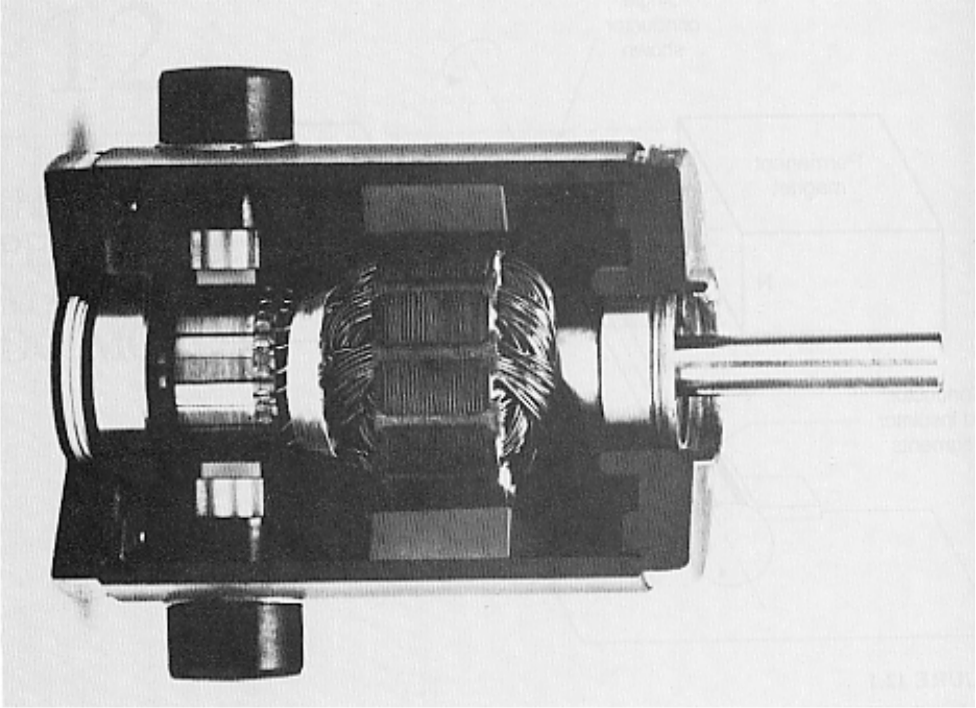
actuator types



Burdea

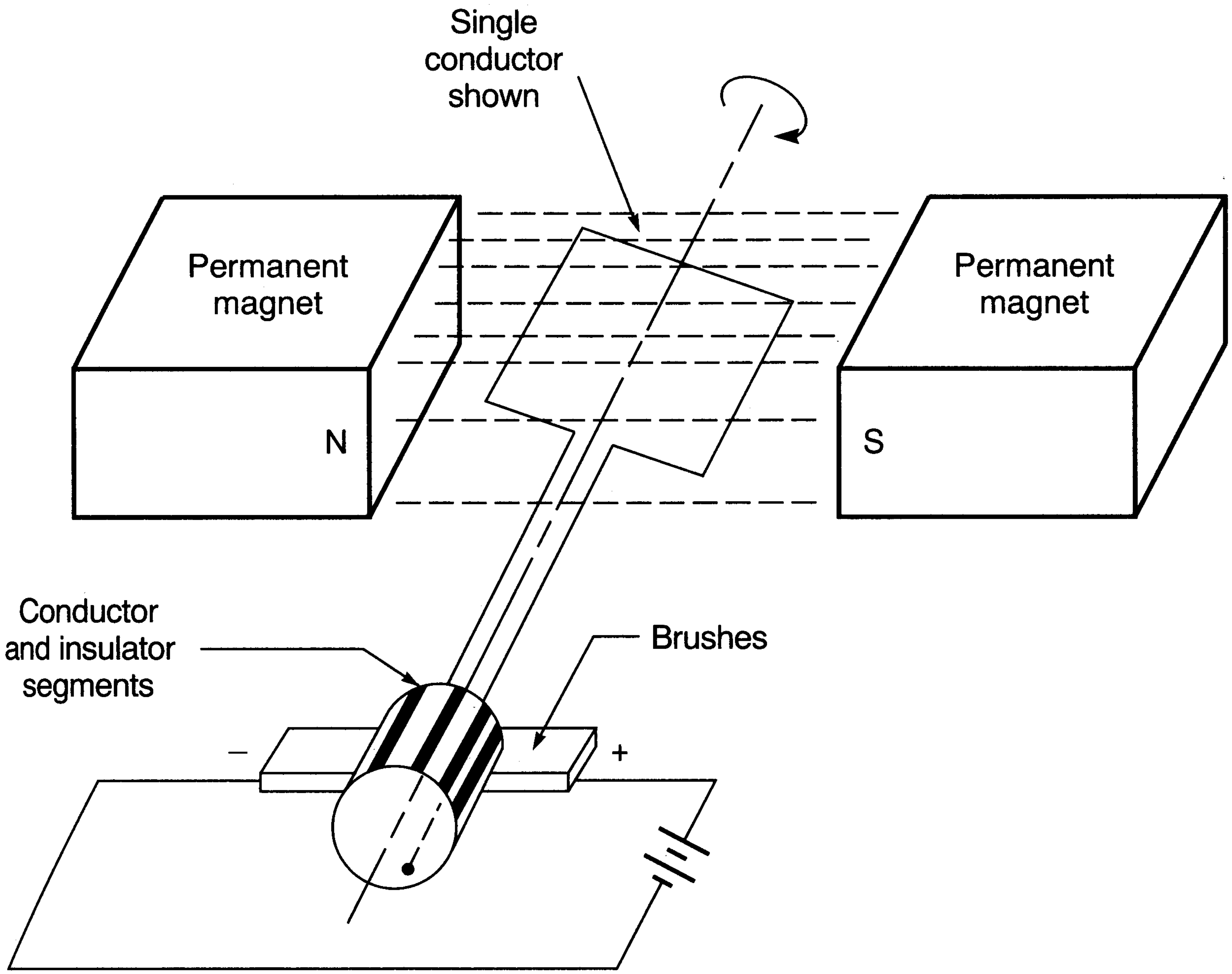
PM DC brushed motors

- rotating *armature* with coil windings is caused to rotate relative to a permanent magnet



- current is transmitted through brushes to armature, and is constantly switched so that the armature magnetic field remains fixed.

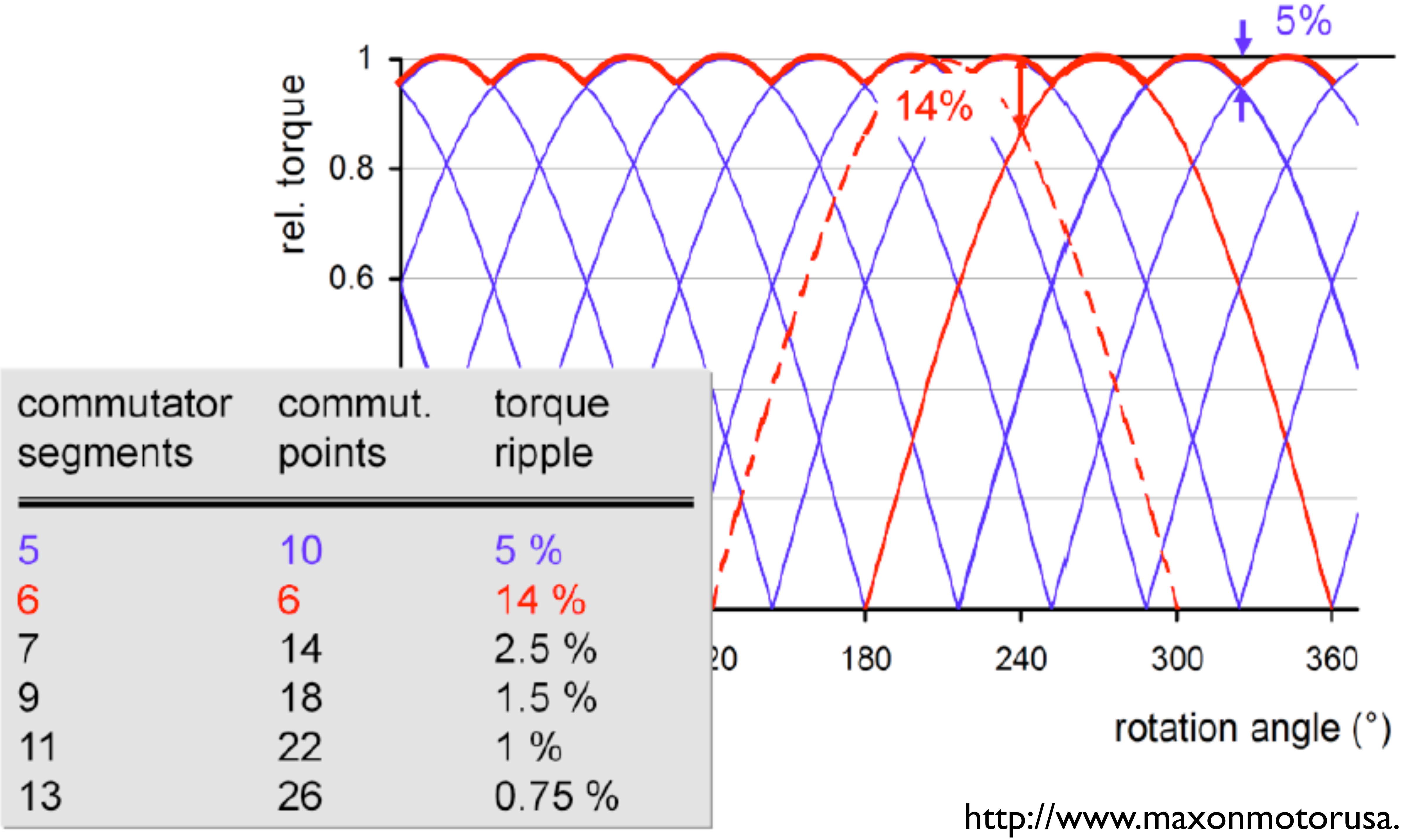
DC motor components



DC motor terms

- cogging/torque ripple
  - tendency for torque output to ripple as the brushes transfer power
- friction/damping
  - caused by bearings, brushes, and eddy currents
- stall torque
  - max torque delivered by motor when operated continuously without cooling

torque ripple



commutator segments	commut. points	torque ripple
5	10	5 %
6	6	14 %
7	14	2.5 %
9	18	1.5 %
11	22	1 %
13	26	0.75 %

http://www.maxonmotorusa.com/

motor equations

- torque constant k_T

$$\tau = k_T i$$

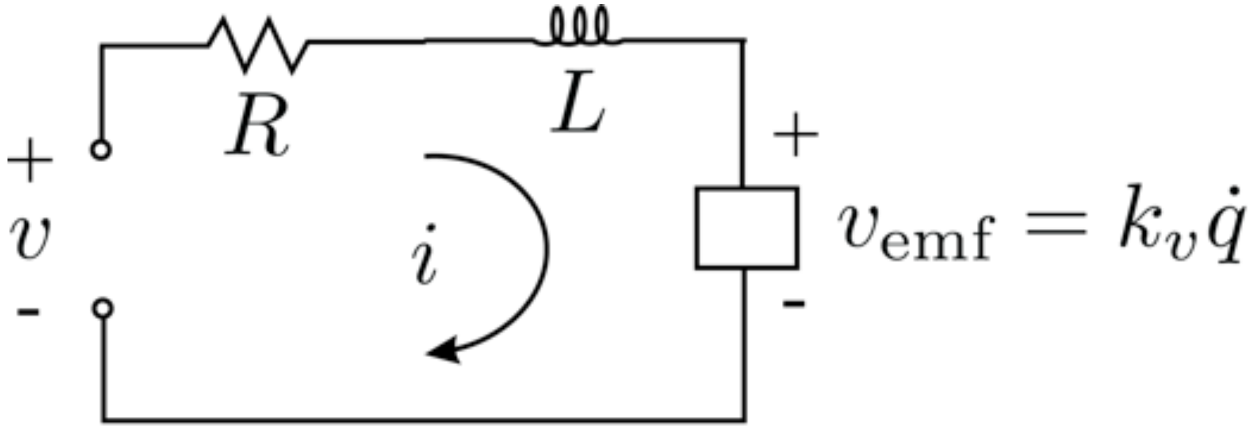
- speed constant k_v

$$v_{\text{emf}} = k_v \dot{q}$$

- dynamic equations

$$v = L\frac{di}{dt} + Ri + v_{\text{emf}}$$

$$m\ddot{q} + b\dot{q} = \tau$$

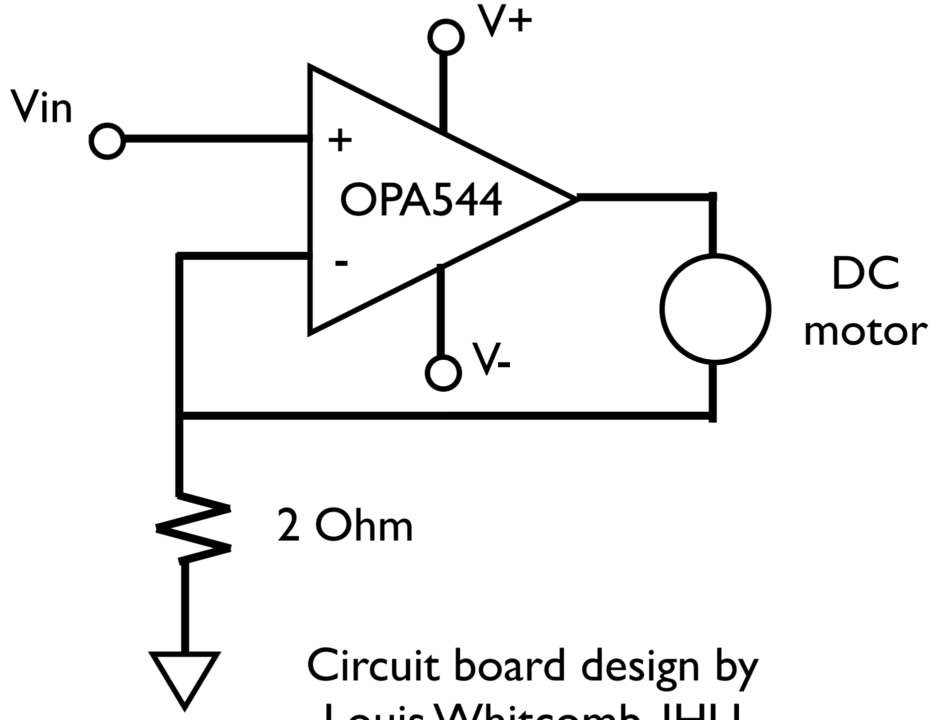


motor amplifier types

current amplifier

(voltage controlled current source VCCS)

directly controls current
current = torque (good!)
expensive



Circuit board design by
Louis Whitcomb, JHU

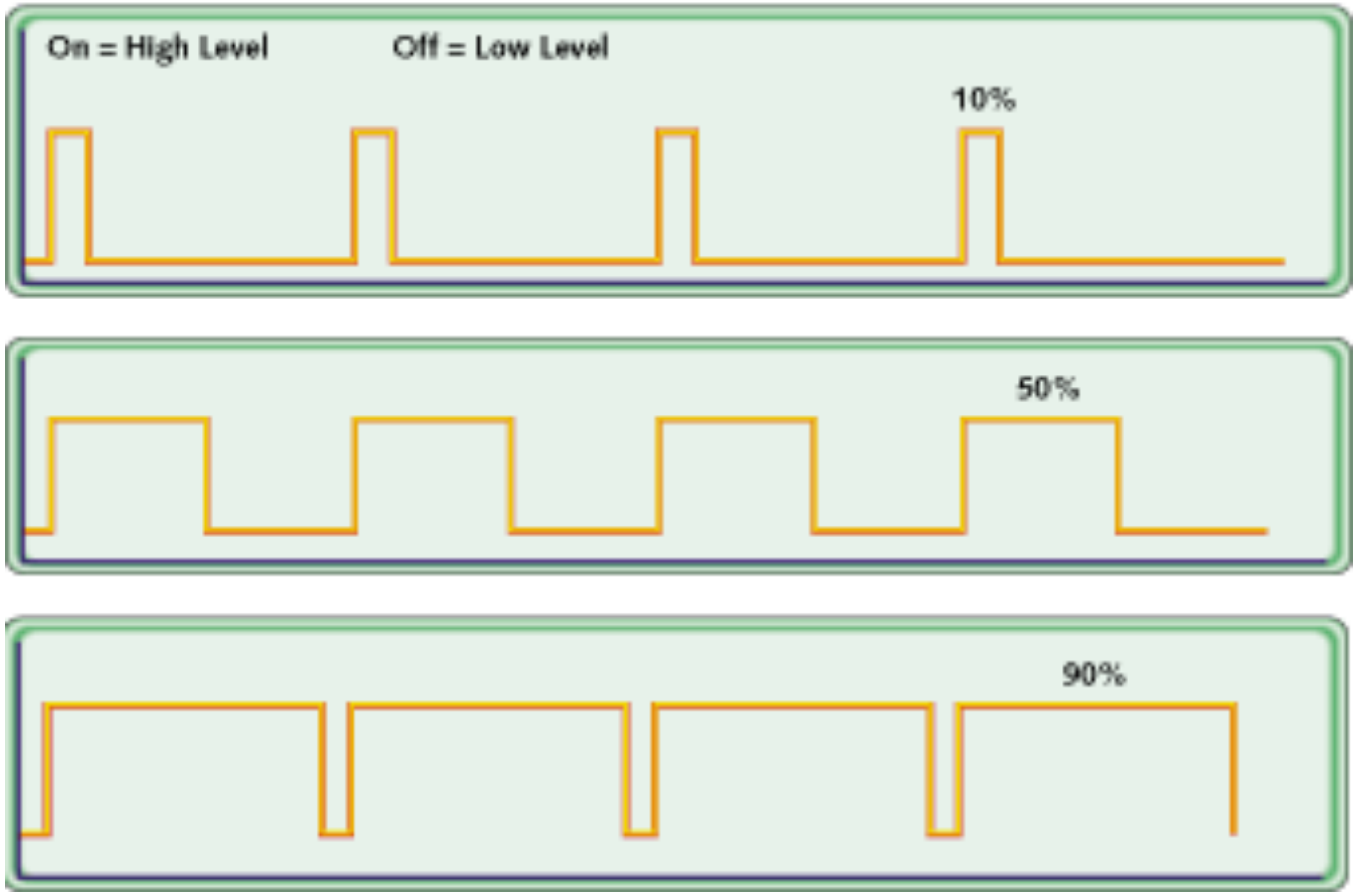
voltage amplifier

(voltage controlled voltage source VCVS)

indirectly controls current
current depends on voltage and state
often less expensive

ardumotor shield
https://www.sparkfun.com/products/9815
based on L298 H-bridge

pulse width modulation



http://www.barrgroup.com/

assumes that the average signal is a constant signal

duty cycle is the proportion of ***on*** time to the ***period***

useful if you do not have a D/A converter to send analog signals to the motor circuit

switching frequency must be much faster than the mechanical dynamics of the system