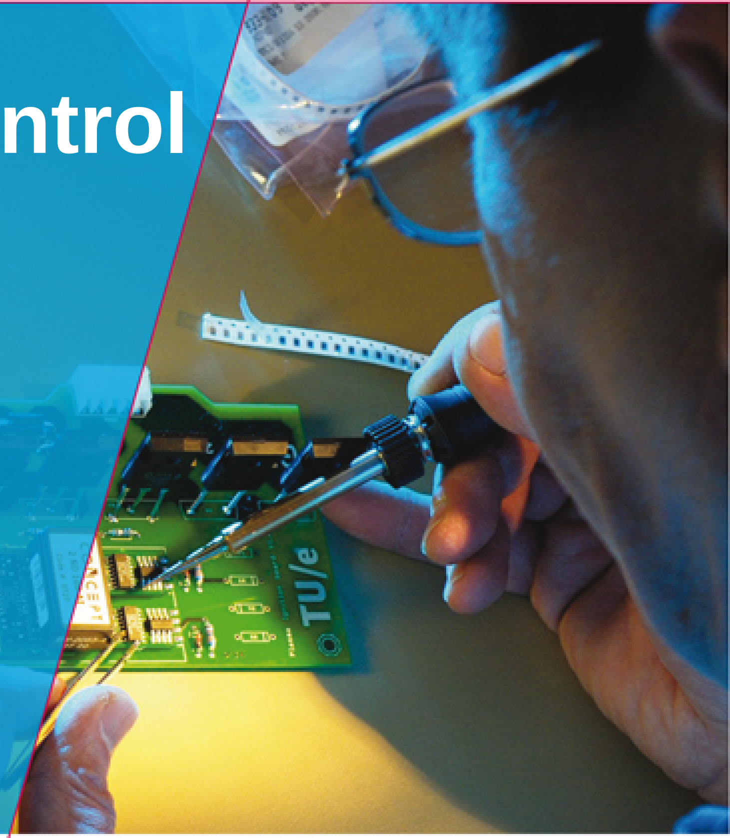
5LIA0 Embedded Vision Control

Feedback Control Systems

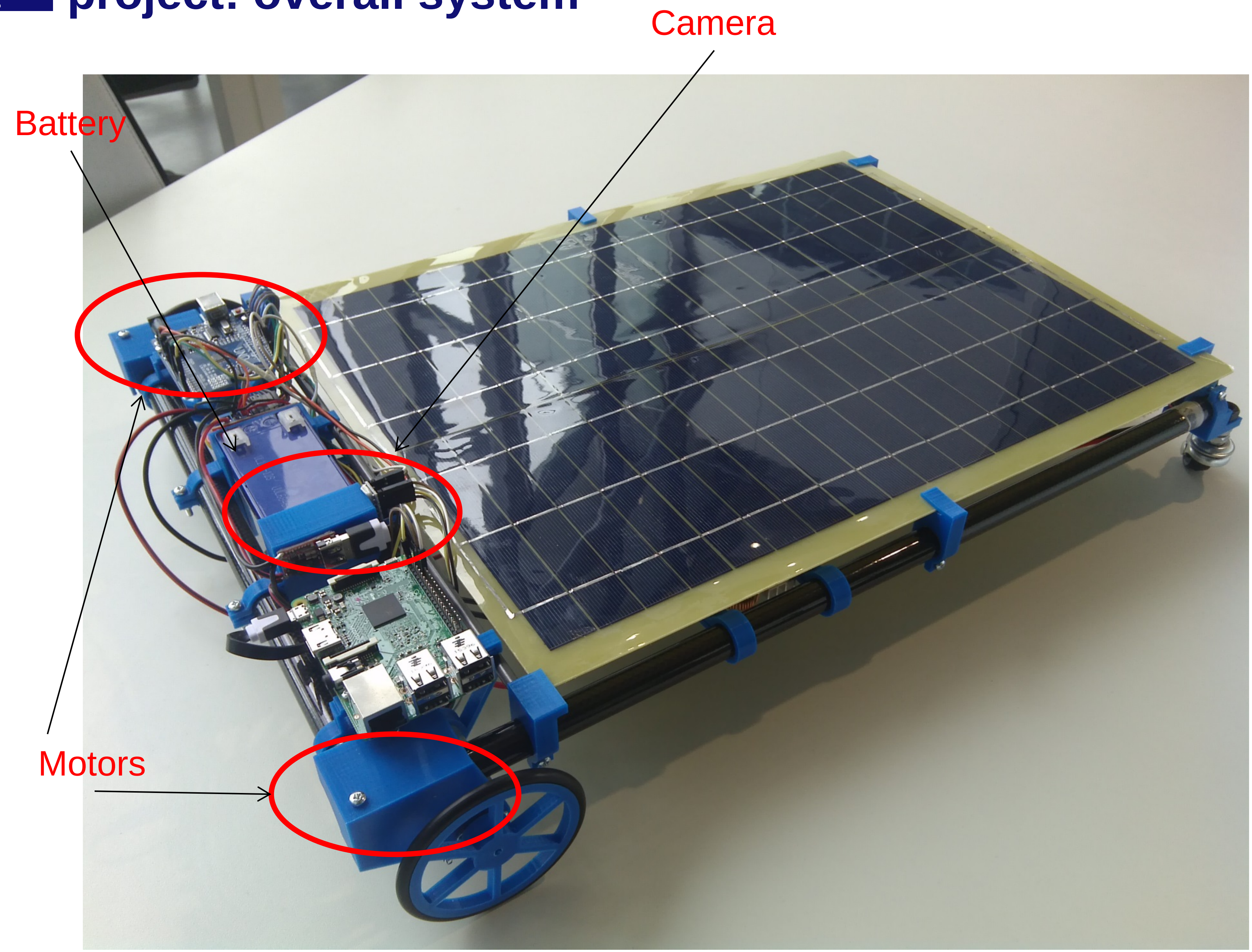
dr. Dip Goswami
d.goswami@tue.nl
Flux 04.135
Department of Electrical Engineering



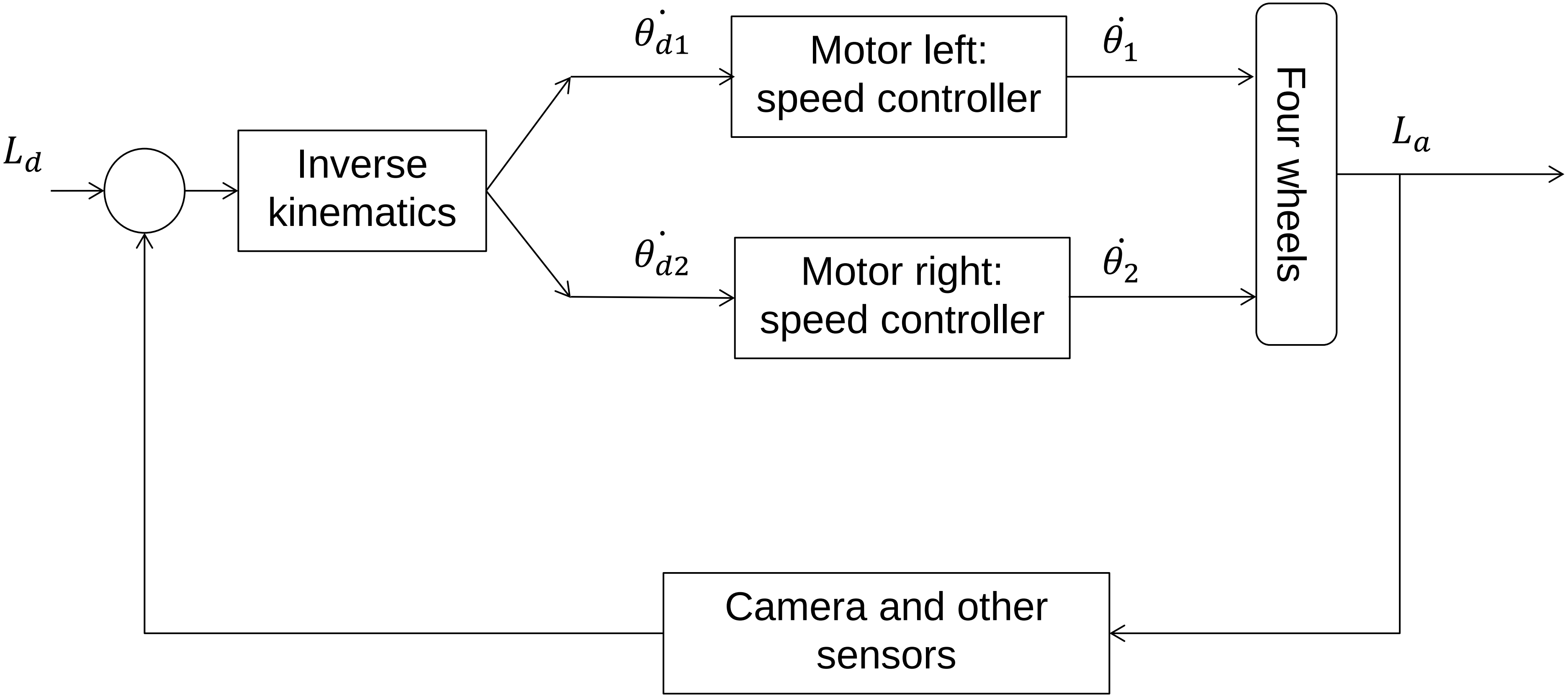
Technische Universiteit
Eindhoven
University of Technology

Where innovation starts

1 project: overall system

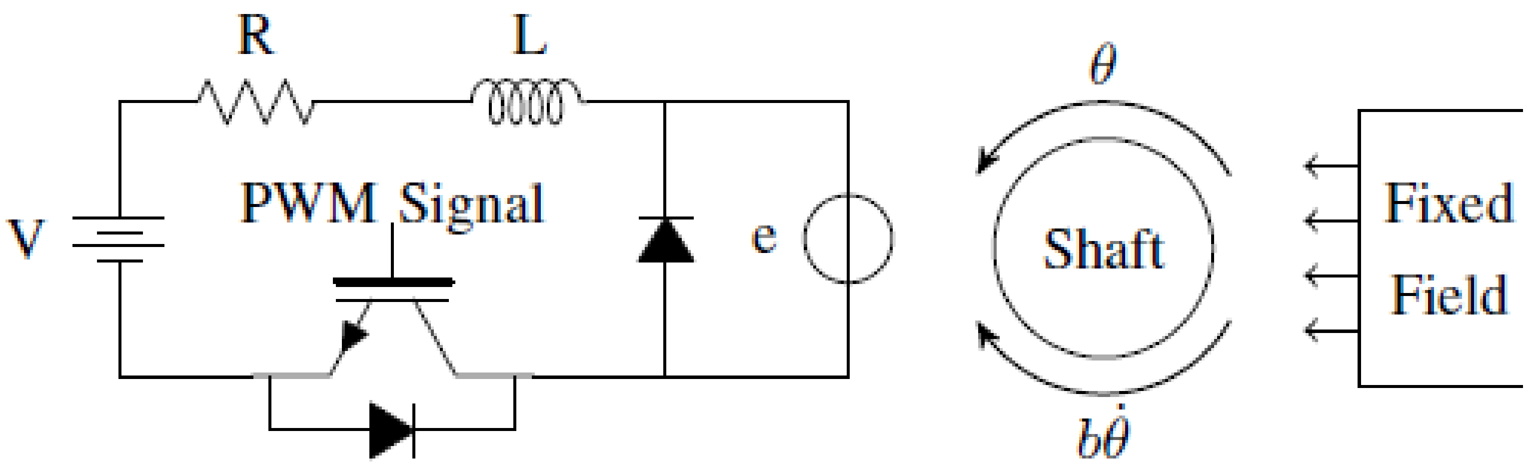


2 overall block diagram



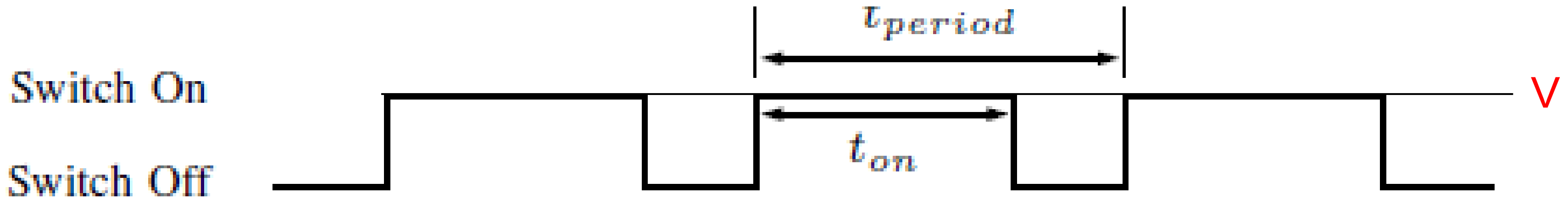
L_a: actual location of vehicle
L_d: desired location of the vehicle

motor speed control: parameters



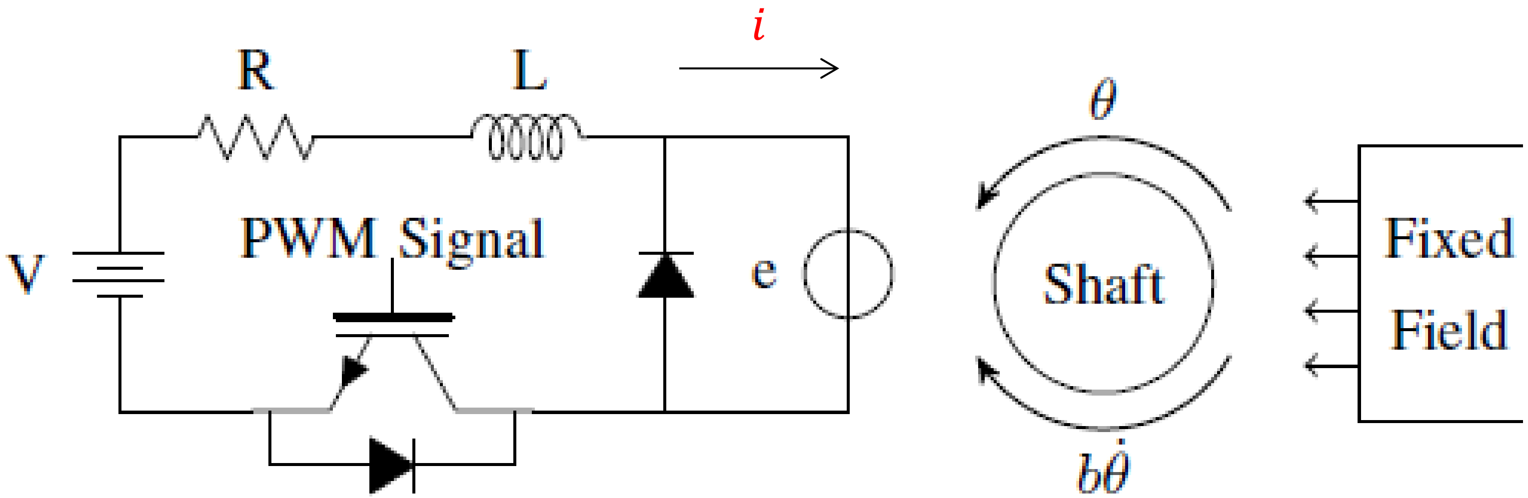
- R: armature resistance
- L: armature reluctance
- V: battery voltage
- θ: shaft position
- $\dot{\theta}$: shaft velocity
- b: frictional constant
- e: back EMF

PWM signal



- Duty cycle $c = \frac{t_{on}}{t_{period}}$
- $0 \le c \le 1$
- $V_{eff} = c.V$

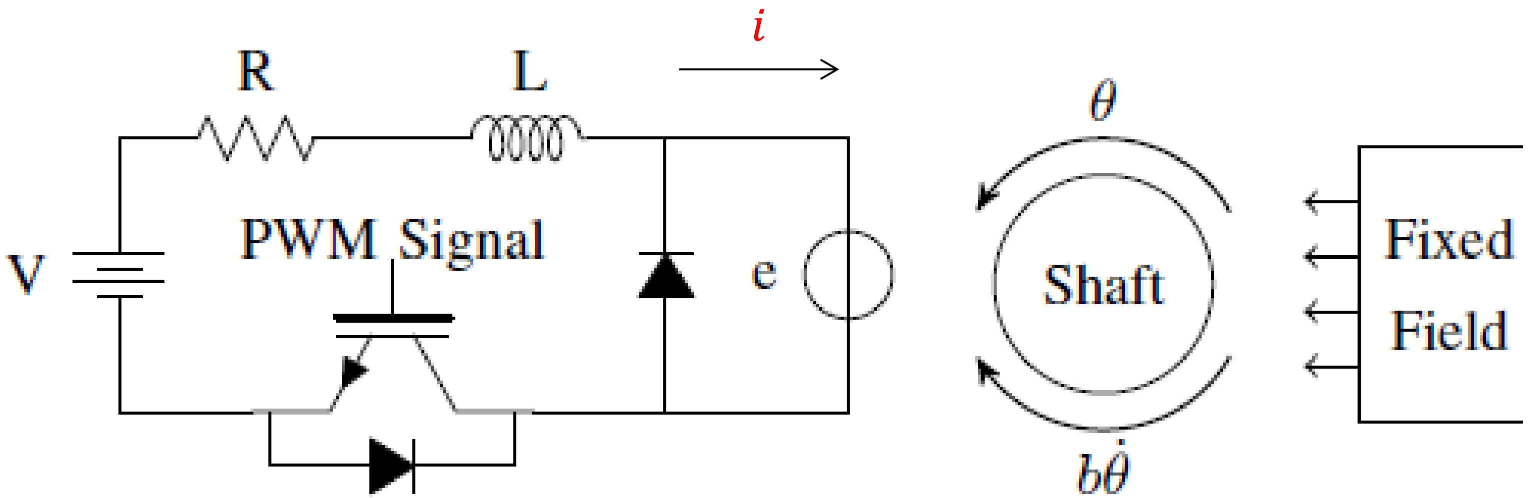
motor speed control: dynamics



- Back EMF $e = K_e\dot{\theta}$
- K_e: Back EMF constant

- Torque at the shaft $T = K_t i$
- K_t: Torque constant

motor speed control: dynamics

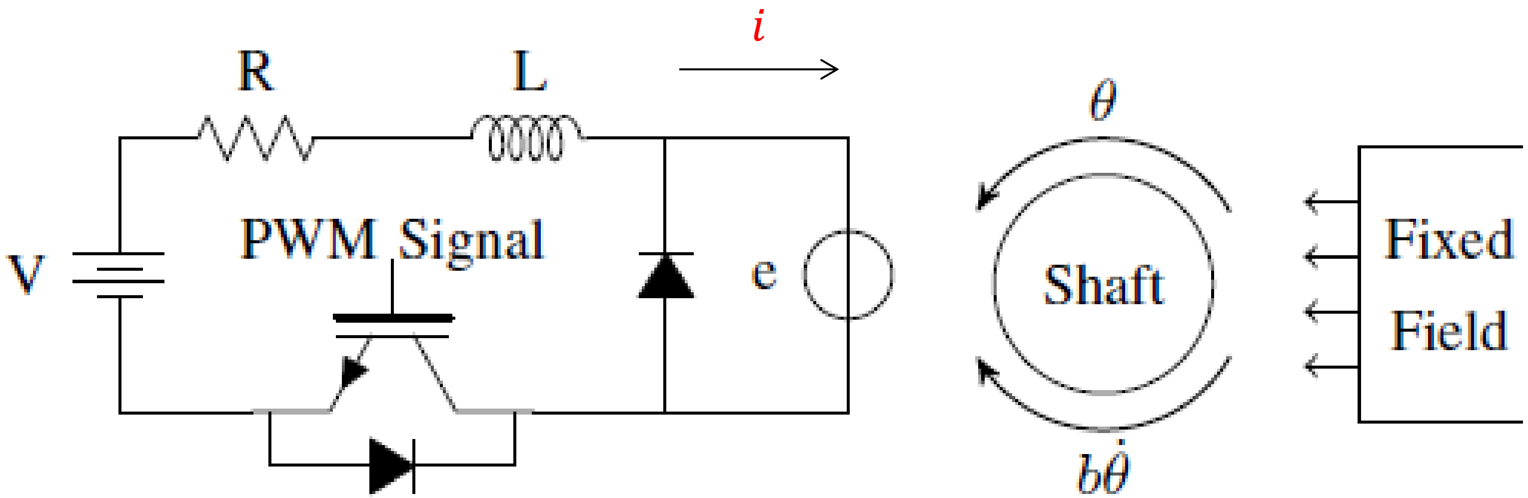


- $J\ddot{\theta} + b\dot{\theta} = K_t . i$
- J: moment of inertia of the motor and load

- $L\frac{di}{dt} + R.i = c.V - K_e.\dot{\theta}$

$$\boxed{\begin{aligned} J\ddot{\theta} + b\dot{\theta} &= K_t . i \\ L\frac{di}{dt} + R.i &= c.V - K_e.\dot{\theta} \end{aligned}}$$

7 motor speed control: state space model

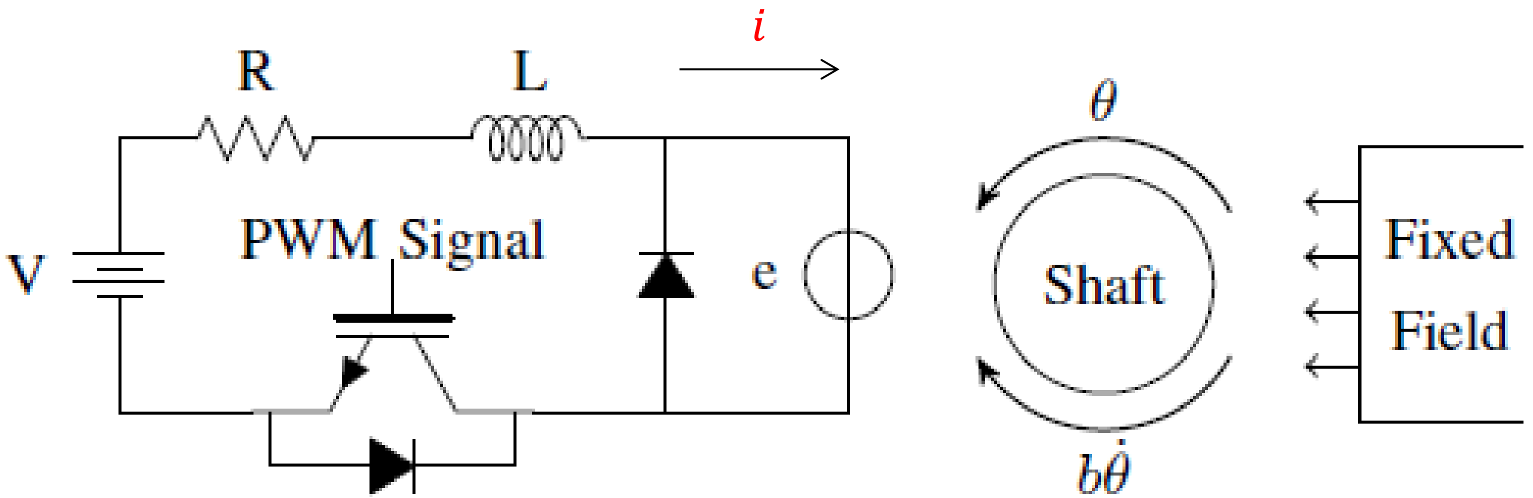


- $\dot{x} = Ax + Bu;\ y = Cx$
- States $\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} \dot{\theta} \\ i \end{bmatrix}$

$$J\ddot{\theta} + b\dot{\theta} = K_t . i$$

$$L\frac{di}{dt} + R.i = c.V - K_e.\dot{\theta}$$

motor speed control: state space model

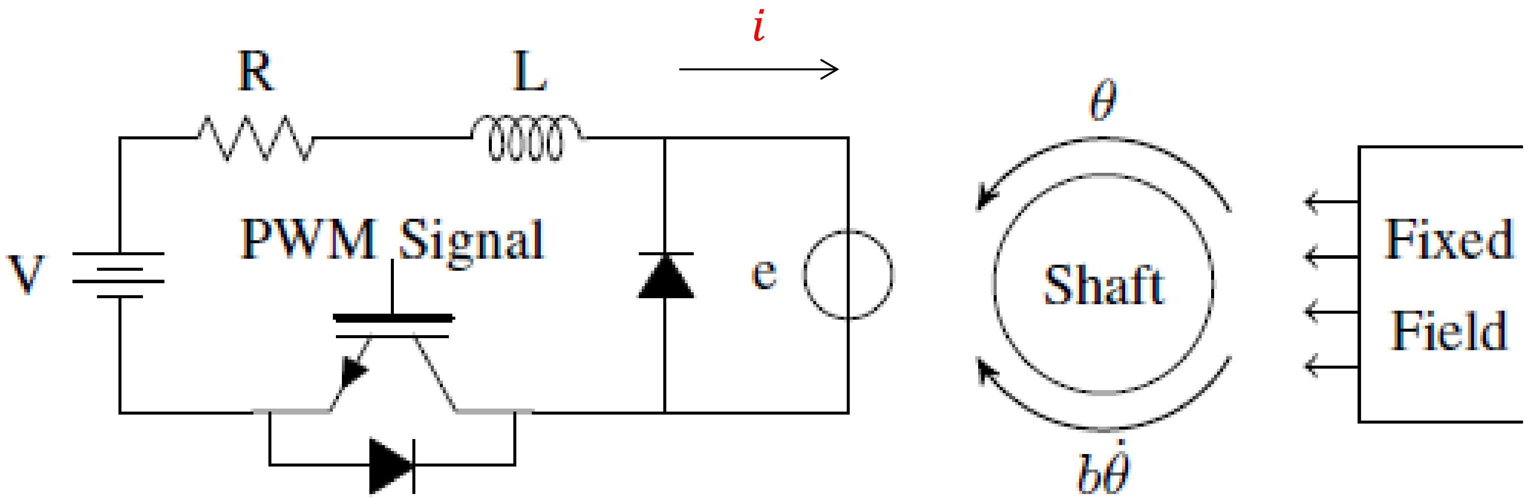


- $\dot{x} = Ax + Bu;\ y = Cx$
- States $\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} \dot{\theta} \\ i \end{bmatrix}$
- $\dot{x}_1 = -\frac{b}{J}x_1 - \frac{K_t}{J}x_2$

$$J\ddot{\theta} + b\dot{\theta} = K_t.i$$

$$L\frac{di}{dt} + R.i = c.V - K_e.\dot{\theta}$$

motor speed control: state space model

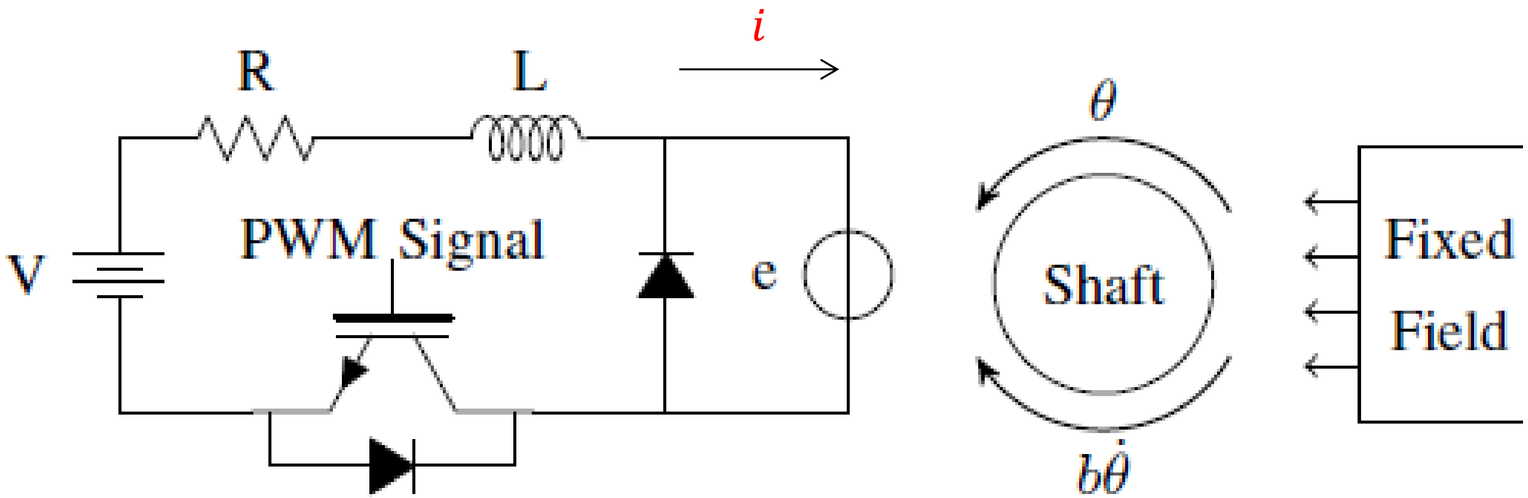


- $\dot{x} = Ax + Bu;\ y = Cx$
- States $\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} \dot{\theta} \\ i \end{bmatrix}$
- $\dot{x}_1 = -\frac{b}{J}x_1 + \frac{K_t}{J}x_2$
- $\dot{x}_2 = -\frac{K_e}{L}x_1 - \frac{R}{L}x_2 \ + c.\frac{V}{L}$

$$J\ddot{\theta} + b\dot{\theta} = K_t.i$$

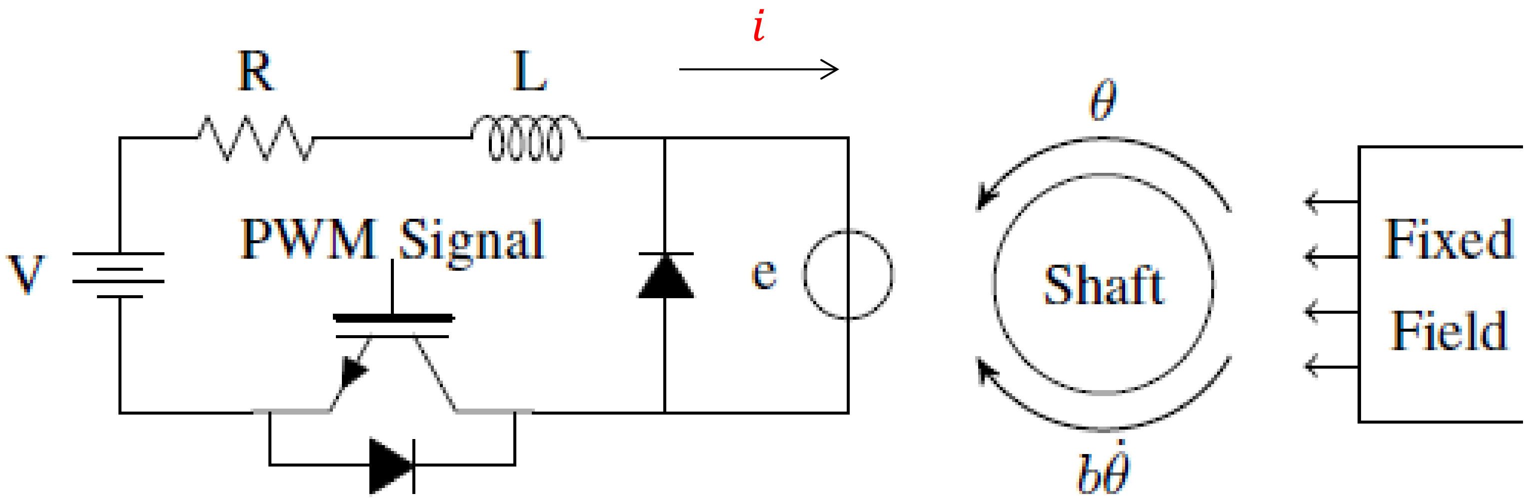
$$L\frac{di}{dt} + R.i = c.V - K_e.\dot{\theta}$$

motor speed control: state space model



- $\dot{x} = Ax + Bu; \; y = Cx$
- $\dot{x}_1 = -\frac{b}{J}x_1 + \frac{K_t}{J}x_2$
- $\dot{x}_2 = -\frac{K_e}{L}x_1 - \frac{R}{L}x_2 \; + c.\frac{V}{L}$
- $\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} -\frac{b}{J} & +\frac{K_t}{J} \\ -\frac{K_e}{L} & -\frac{R}{L} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{V}{L} \end{bmatrix}.\mathrm{c}$

motor speed control: state space model



- $\dot{x} = Ax + Bu;\ y = Cx$
- $\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} -\frac{b}{J} & +\frac{K_t}{J} \\ -\frac{K_e}{L} & -\frac{R}{L} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{V}{L} \end{bmatrix} . c$
- $y = \dot{\theta} = [1 \quad 0] \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$

12 motor speed control: parameter identification

- $\dot{x} = Ax + Bu;\ y = Cx$
- $\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} -\frac{b}{J} & +\frac{K_t}{J} \\ -\frac{K_e}{L} & -\frac{R}{L} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{V}{L} \end{bmatrix} . \mathrm{c}$
- $y = \dot{\theta} = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$

- Example:
  - J = 0.0015 Kgm^2;
  - b = 0.03 Nms;
  - K_t = 0.1 Nm/A;
  - K_e = 0.1 V/rad.s;
  - R = 1 Ohm;
  - L = 0.01H;
  - V = 12V;

motor speed control: parameter identification

- J = 0.0015 Kgm^2;
- b = 0.03 Nms;
- K_t = 0.1 Nm/A;
- K_e = 0.1 V/rad.s;
- R = 1 Ohm;
- L = 0.01H;
- V = 12V;

- $\dot{x} = Ax + Bu; \; y = Cx$
- $\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} -20.0000 & -66.6667 \\ -10.0000 & -100.0000 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 1200 \end{bmatrix} . \mathrm{c}$
- $y = \dot{\theta} = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$

controller design (details: homologation lectures)

Continuous-time

$$\boxed{\dot{x} = Ax + Bu;\ y = Cx}$$

Sampling period = h

Discrete-time

$$\boxed{x[k+1] = \Phi x[k] + \Gamma u[k]}$$

Controller

$$\boxed{u[k] = Kx[k] + F.r}$$

K= feedback gain,
F = feedforward gain

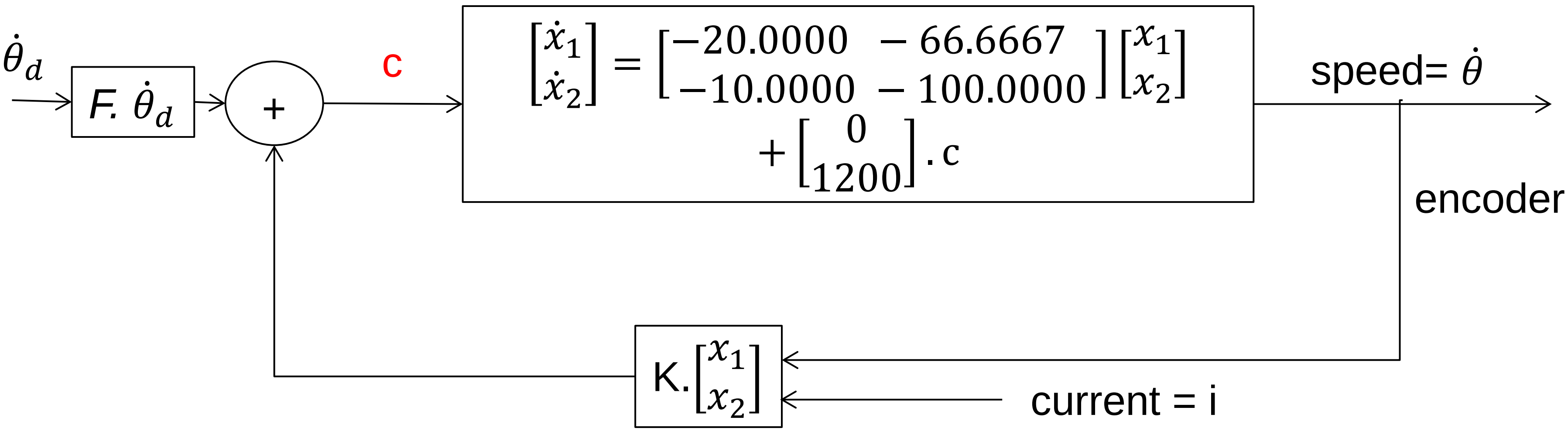
Check controllability of (ϕ,Γ) $\rightarrow$ must be controllable. γ must be invertible.

$$\gamma = \begin{bmatrix} \Gamma & \phi\Gamma & \phi^2\Gamma & \cdots & \phi^{n-1}\Gamma \end{bmatrix}$$

Feedback gain $K = -[0 \quad 0 \quad \dots \quad 1]\gamma^{-1}H(\alpha), \alpha = pole\ locations$

Feedforward gain $F = \frac{1}{C(I-\phi-\Gamma K)^{-1}\Gamma}$

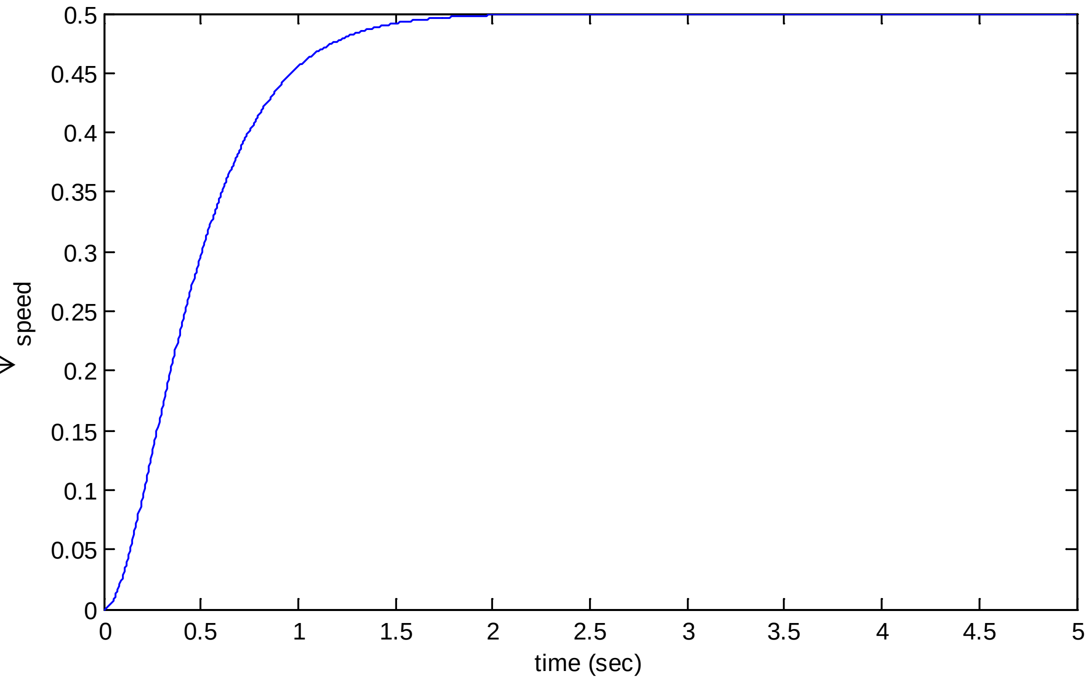
speed control loop



speed control loop: design considerations

Sampling period = 5ms
Battery voltage = 12V
$\dot{\theta}_d$= 0.5 rad/s

Pole locations: 0.98, 0.98

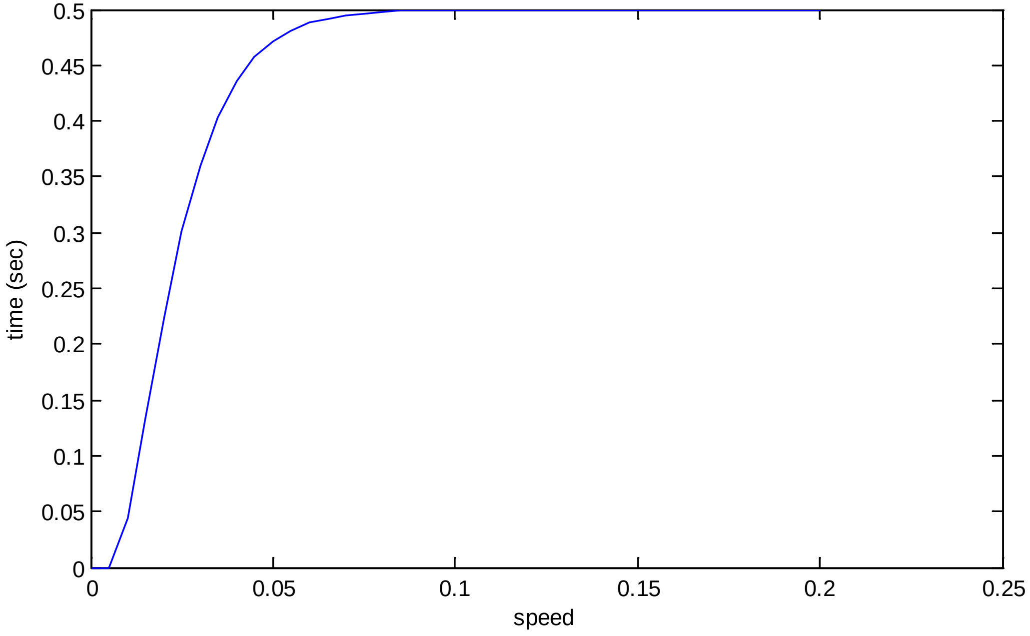


Settling time = 2sec
Max(c) = 0.0083

speed control loop: design considerations

Sampling period = 5ms
Battery voltage = 12V
$\dot{\theta}_d$= 0.5 rad/s

Pole locations: 0.6, 0.6

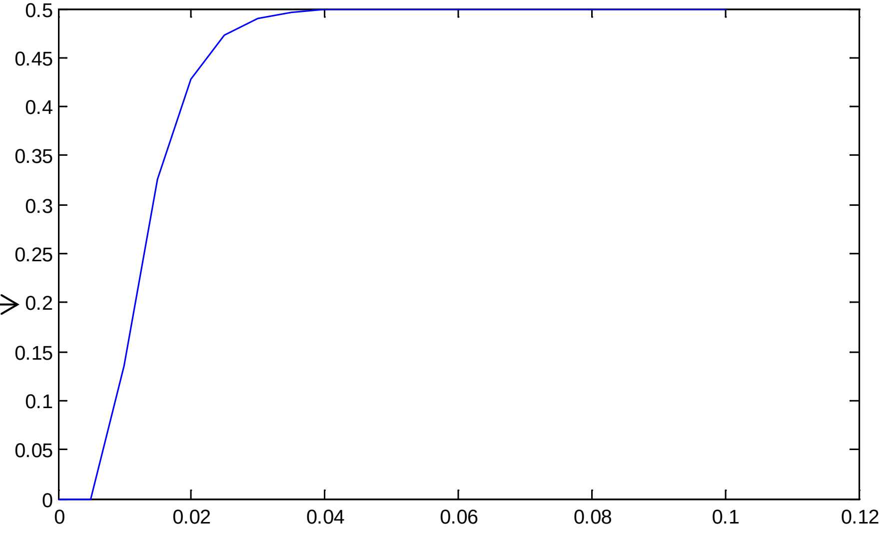


Settling time = 0.075sec
Max(c) = 0.0533

speed control loop: design considerations

Sampling period = 5ms
Battery voltage = 12V
$\dot{\theta}_d$= 0.5 rad/s

Pole locations: 0.3, 0.3

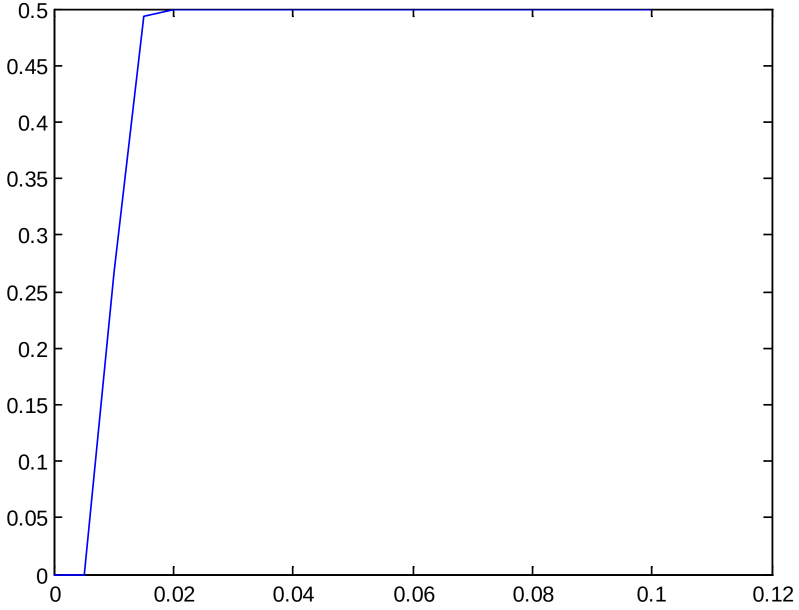


Settling time = 0.04sec
Max(c) = 0.1634

speed control loop: design considerations

Sampling period = 5ms
Battery voltage = 12V
$\dot{\theta}_d$= 0.5 rad/s

Pole locations: 0.01, 0.02

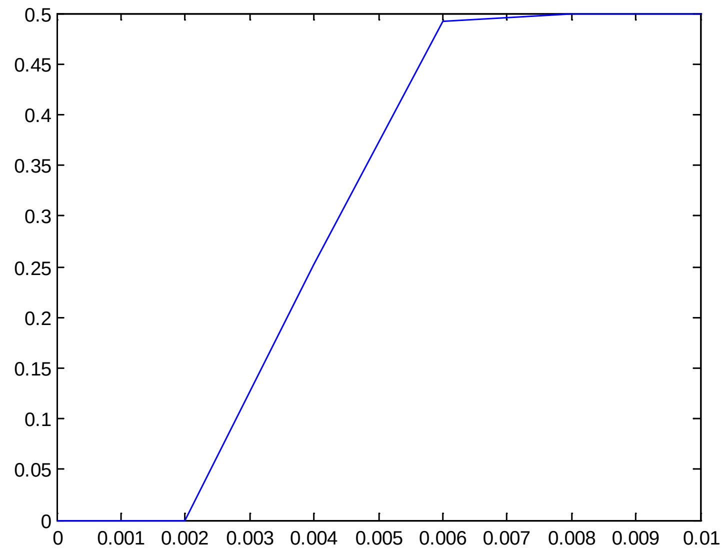


Settling time = 0.02sec
Max(c) = 0.3234

speed control loop: design considerations

Sampling period = 2ms
Battery voltage = 12V
$\dot{\theta}_d$= 0.5 rad/s

Pole locations: 0.01, 0.02

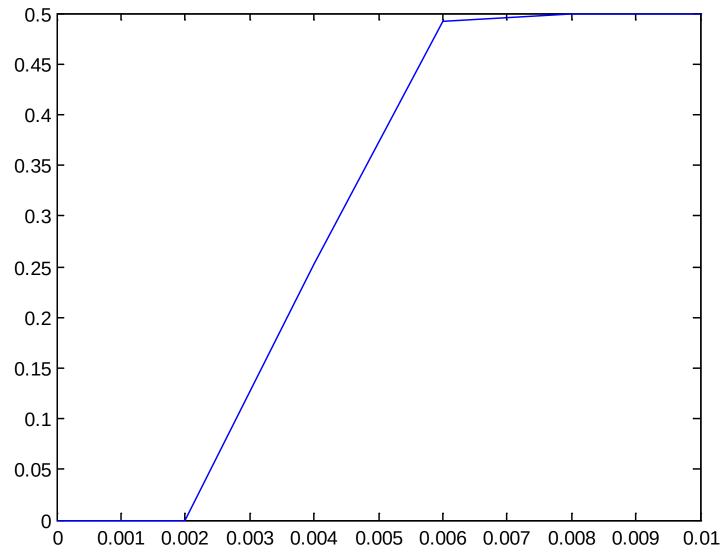


Settling time = 0.008sec
Max(c) = 1.7059

speed control loop: design considerations

Sampling period = 2ms
Battery voltage = 12V
$\dot{\theta}_d$= 0.5 rad/s

Pole locations: 0.2, 0.3



Settling time = 0.015sec
Max(c) = 0.98

design considerations: summary

- Relation between:
  - Sampling period
  - Maximum input
  - Setting time

multi-loop control