CS65K Robotics

Modelling, Planning and Control

Chapter 5: Sensors and Actuators

LECTURE 10: SENSORS AND ACTUATORS

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Objectives

- Move forward from Manipulator to sensor and actuators.
- The model of a **servomotor** with power amplifier is derived
- **Velocity control (v)** vs **torque control(ω)** of the electric drive system are presented
- The effects of mechanical transmission are analyzed
- The general scheme for control of an electric drive system is introduced

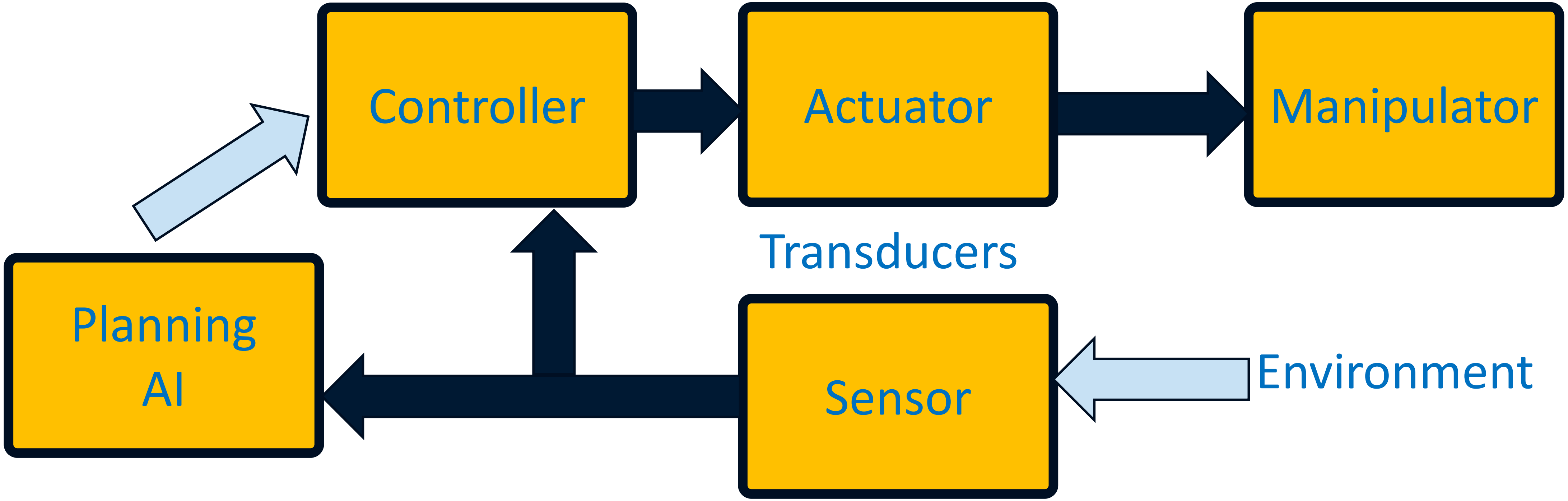
Objectives

- The motion control problem for robot manipulators is formulated
- The two techniques for joint space control are introduced
- The **dynamic model** is cast in a suitable form for decentralized control

Overview

SECTION 1

Logical Units for A Robot



Sensors

SECTION 2

Sensor

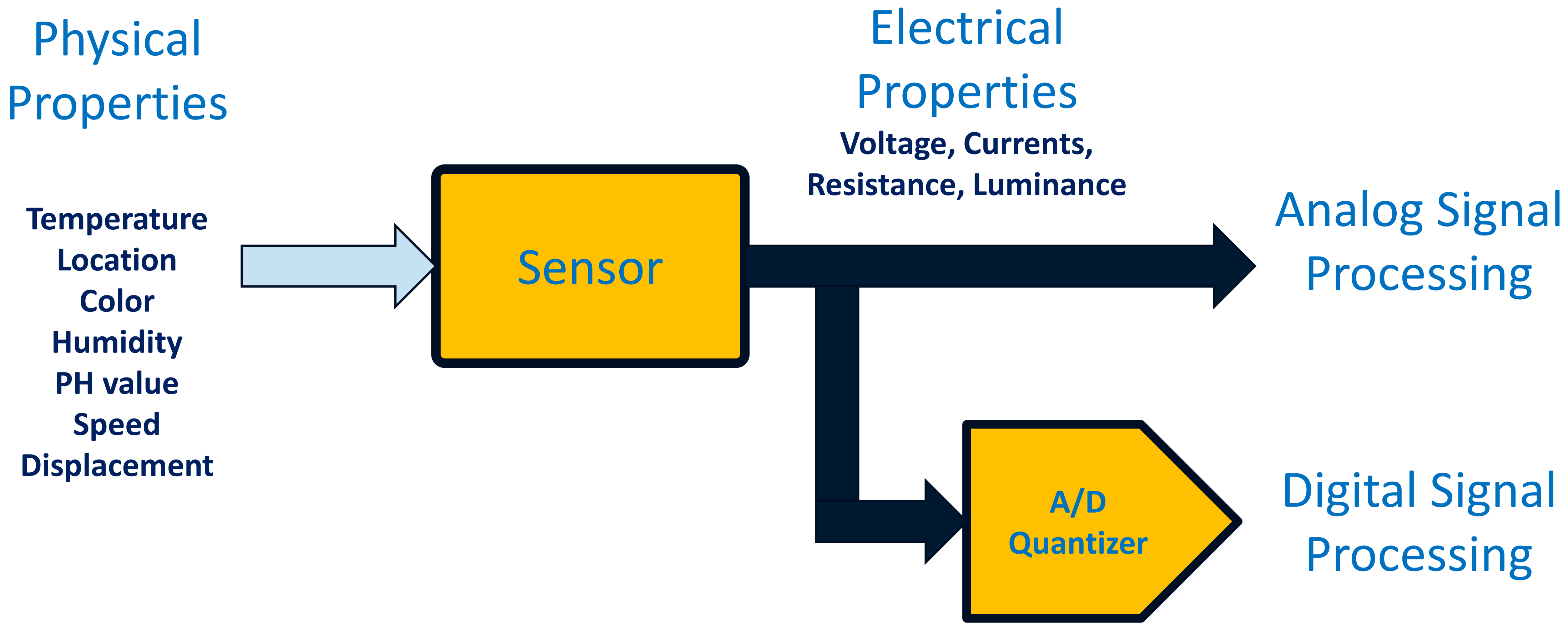
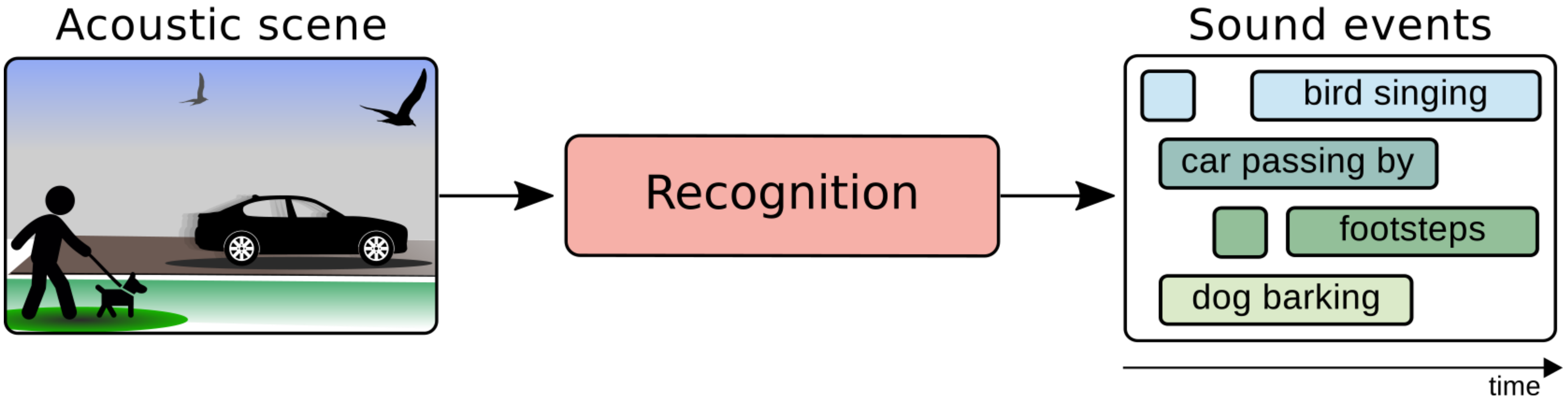

Physical Properties
Temperature
Location
Color
Humidity
PH value
Speed
Displacement
Sensor
Electrical Properties
Voltage, Currents, Resistance, Luminance
Analog Signal Processing
A/D Quantizer
Digital Signal Processing

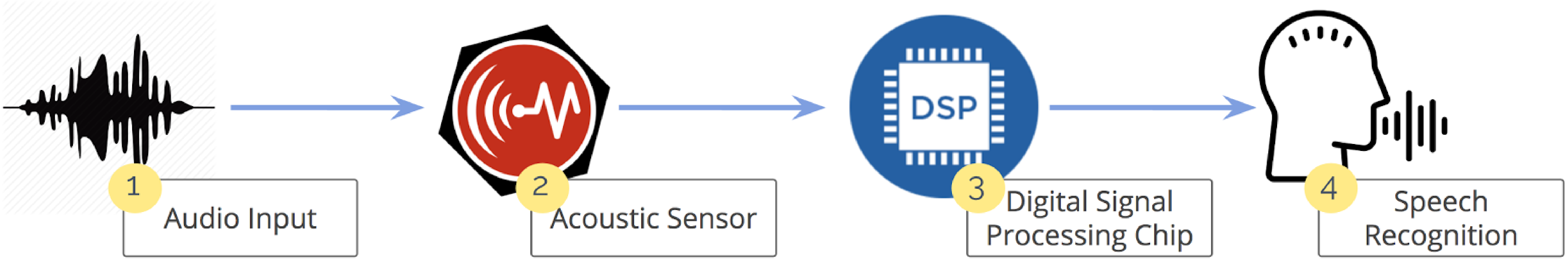
Image Processing

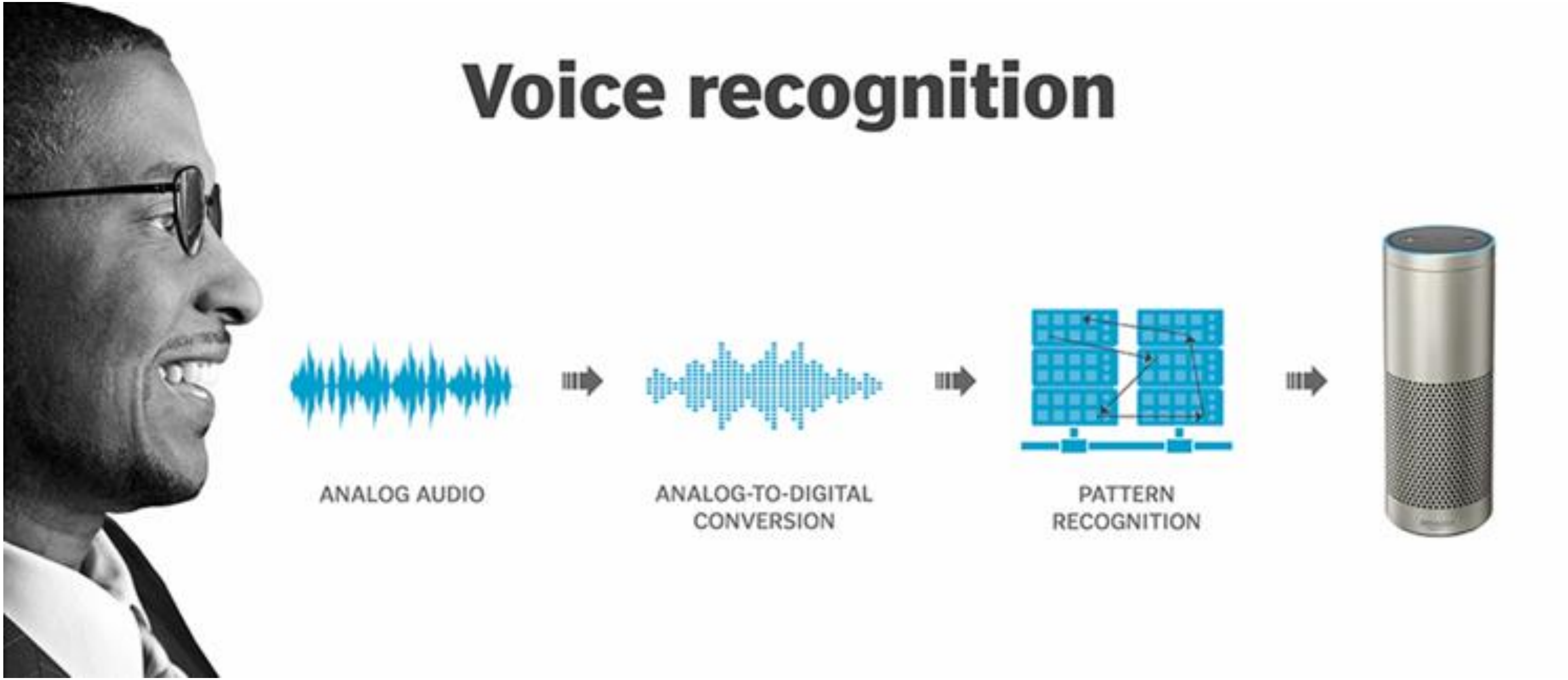
Type	Input	Output	Examples
Low Level Process	Image	Image	Noise removal, image sharpening
Mid-Level Process	Image	Attributes	Object recognition, Segmentation
High Level Process	Attributes	Understanding	Scene understanding, autonomous navigation

Image Vision

Low-level Vision	Luminance Color Spatial freq. Temporal freq. Local Motion	Low-level coding
Mid-level Vision	Textures Surfaces Lighting Global motion Depth	Mid-level coding
High-level vision	Objects Characters Actions Intentions	High-level coding


Acoustic scene
Recognition
Sound events
bird singing
car passing by
footsteps
dog barking
time


1
Audio Input
2
Acoustic Sensor
DSP
3
Digital Signal Processing Chip
4
Speech Recognition


Voice recognition
ANALOG AUDIO
ANALOG-TO-DIGITAL
CONVERSION
PATTERN
RECOGNITION

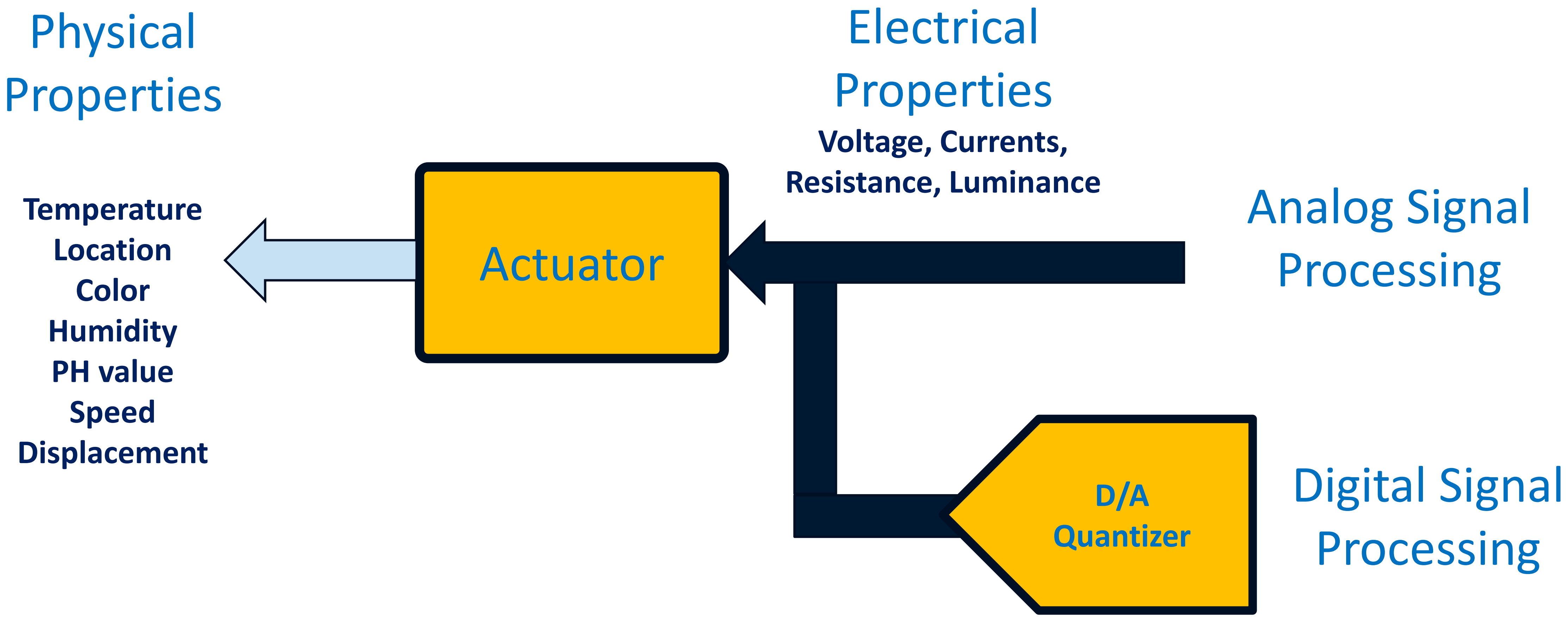
Purpose of Sensors

- To give robot information about itself. (Joint angle, connection status)
- To give robot information about the environment.

Actuators

SECTION 3

Actuators



Physical Properties
Temperature
Location
Color
Humidity
PH value
Speed
Displacement
Actuator
Electrical Properties
Voltage, Currents, Resistance, Luminance
Analog Signal Processing
D/A Quantizer
Digital Signal Processing

Transducers

Physical Properties

Temperature
Location
Color
Humidity
PH value
Speed
Displacement

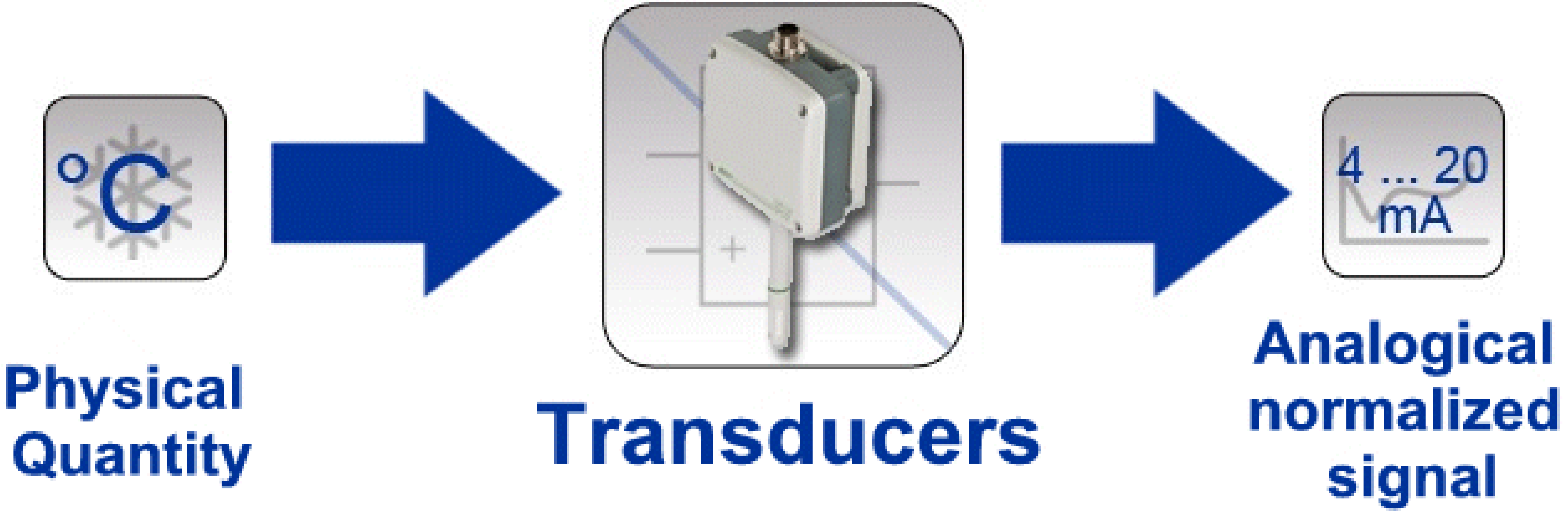
Transducers

Sensor

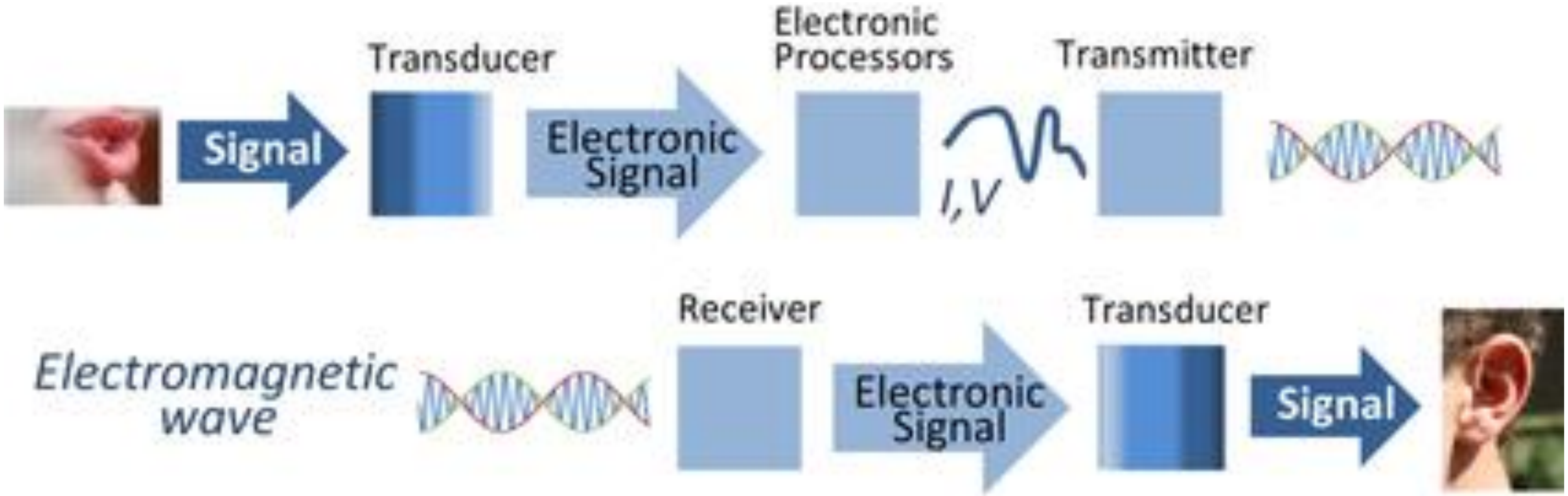
Actuator

Electrical Properties

Voltage, Currents, Resistance, Luminance



Transducers



Transducer
Electronic
Processors
Transmitter
Signal
Electronic
Signal
I,V
Receiver
Transducer
Electromagnetic
wave
Electronic
Signal
Signal

End Effectors

- In robotics, an end effectors are the device or tool that's connected to the end of a robot arm end enables the robot arm to perform specific task
- Usually end effectors are custom engineered for a particular task

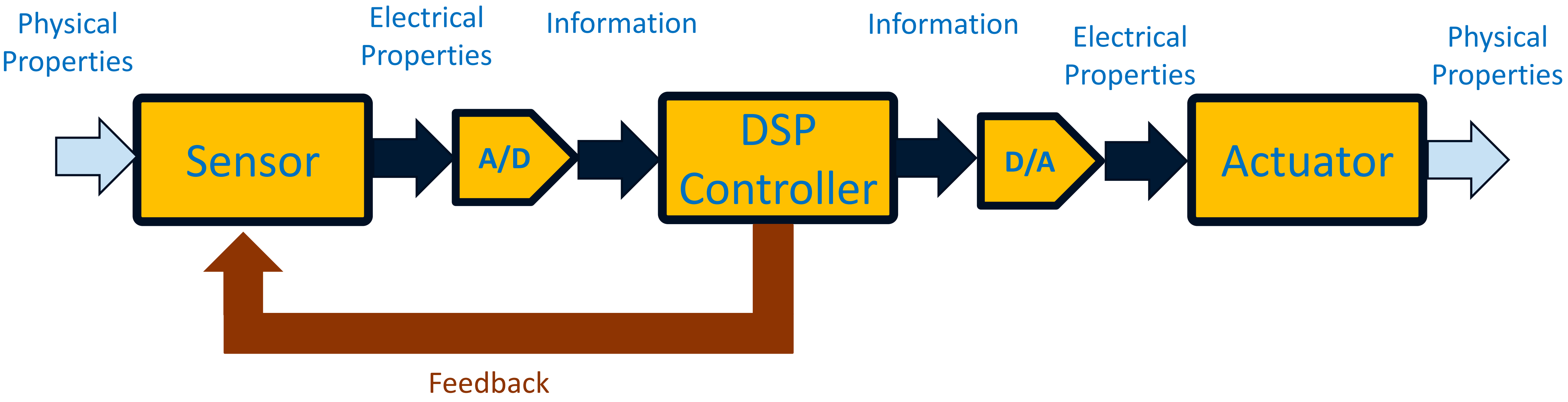



End-to-End Model

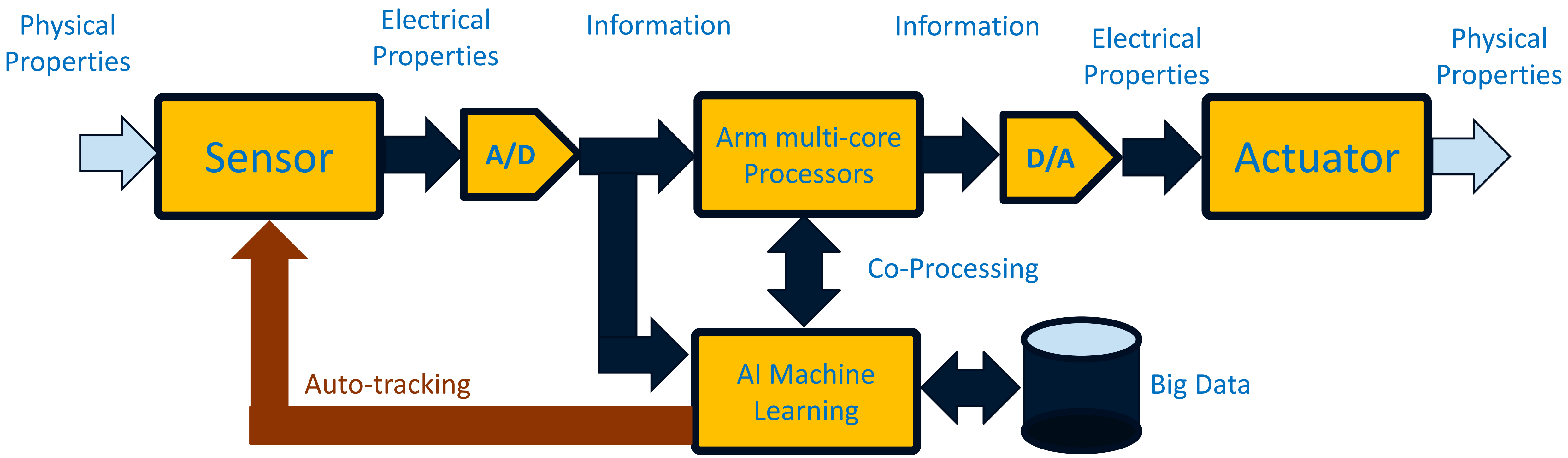
SECTION 4

End-to-End Robot Model

End-to-End DSP Robot Model



End-to-End Smart Robot Model



Model of Electric Drive System

SECTION 5

Model of Electric Drive System

From a modelling viewpoint, a permanent-magnet DC motor and a brushless DC motor provided with the commutation module and position sensor can be described by the same differential equations

Electric servomotor with amplifier

- Electric balance

$$V_a = (R_a + sL_a)I_a + V_g$$

$$V_g = k_v \Omega_m$$

- Mechanical balance

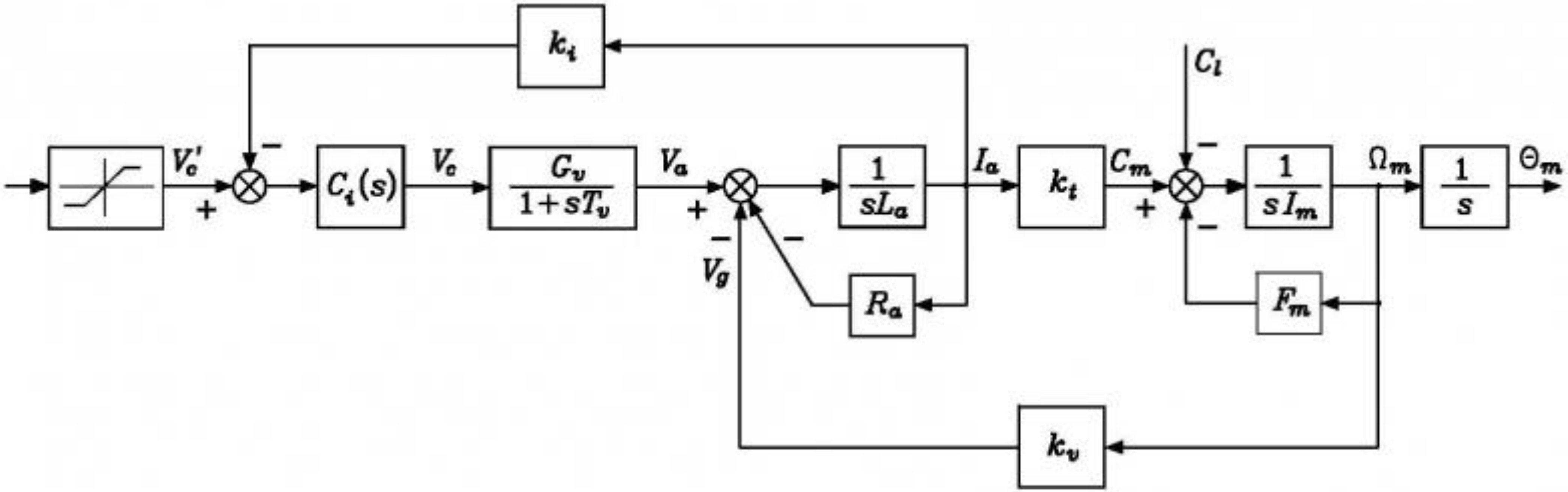
$$C_m = (sI_m + F_m)\Omega_m + C_l$$

$$C_m = k_t I_a$$

- Power amplifier

$$\frac{V_a}{V_c} = \frac{G_v}{1 + sT_v}$$

- Possibility of armature *current feedback*



Block scheme of an electric drive

Velocity-Controlled Generator

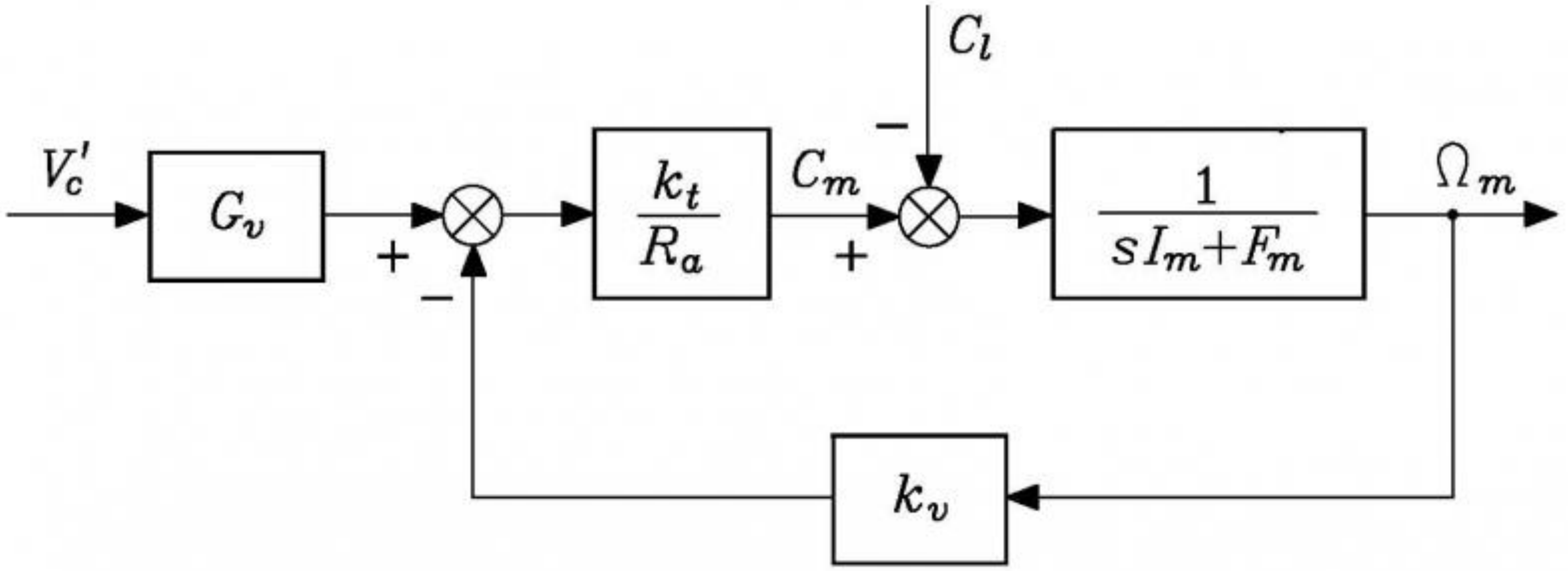
The choice of the regulator $C_i(s)$ of the current loop allows a velocity-controlled or torque-controlled behaviour for the electric drive, depending on the values attained by the loop gain

- $k_i = 0$
- $F_m \ll \dfrac{k_v k_t}{R_a}$

$$\Omega_m = \frac{\dfrac{1}{k_v}}{1 + s\dfrac{R_a I_m}{k_v k_t}} G_v V_c' - \frac{\dfrac{R_a}{k_v k_t}}{1 + s\dfrac{R_a I_m}{k_v k_t}} C_l$$

- At steady state

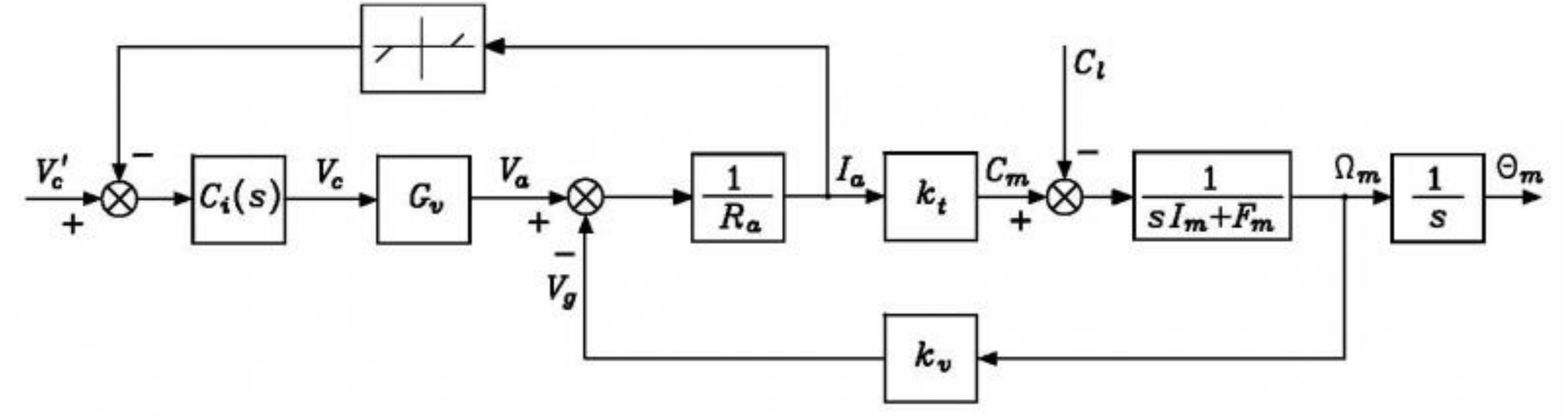
$$\omega_m \approx \frac{G_v}{k_v} v_c'$$



Block scheme of an electric drive as a velocity-controlled generator

Current Protection

- Setting a protection can be solved by introducing a current limit that is not performed by a saturation on the control signal but it exploits a current feedback with a dead-zone nonlinearity on the feedback path



Block scheme of an electric drive with nonlinear current feedback

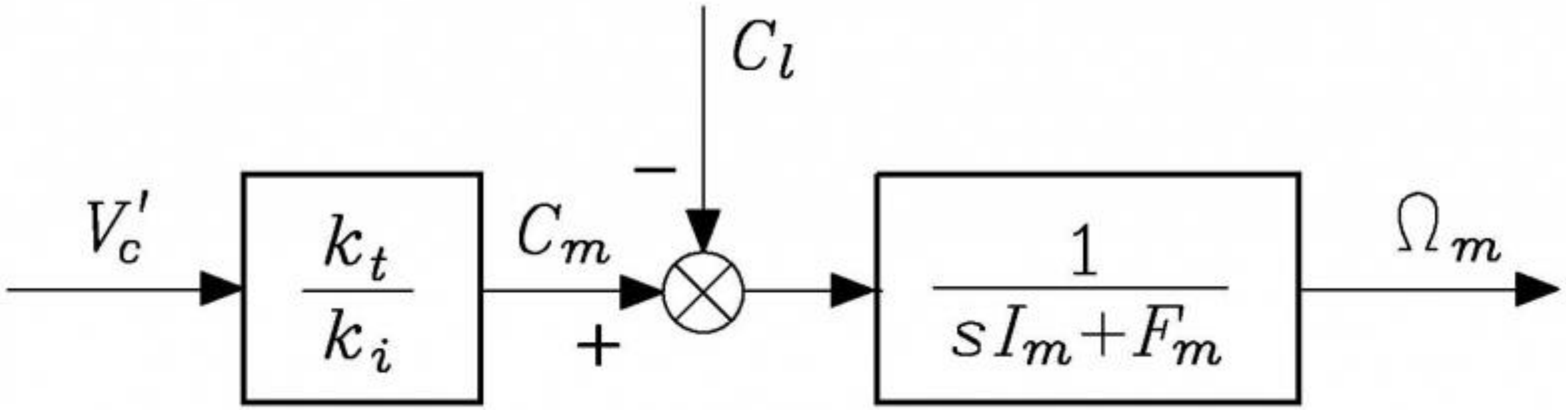
Torque-Controlled Generator

- $Kk_i \gg R_a$
- $k_v \Omega / K k_i \approx 0$

$$\Omega_m = \frac{\dfrac{k_t}{k_i F_m}}{1 + s\dfrac{I_m}{F_m}} V_c' - \frac{\dfrac{1}{F_m}}{1 + s\dfrac{I_m}{F_m}} C_l$$

- At steady state

$$c_m \approx \frac{k_t}{k_i}\left(v_c' - \frac{k_v}{G_v}\omega_m\right)$$



Block scheme of an electric drive as a torque-controlled generator

Electric Drive Transfer Function

Relationship between the control input and the actuator position output

$$M(s) = \frac{k_m}{s(1 + sT_m)}$$

- Velocity-controlled generator $\quad k_m = \frac{1}{k_v} \qquad T_m = \frac{R_a I_m}{k_v k_t}$
- Torque-controlled generator $\quad k_m = \frac{k_t}{k_i F_m} \qquad T_m = \frac{I_m}{F_m}$

Without current feedback, the system has a better rejection of disturbance torques in terms of both equivalent gain $R_a / k_v k_t \ll 1/F_m$ and time response $R_a I_m / k_v k_t \ll I_m / F_m$

Transmission Effect

SECTION 1

Transmission Effects

Ideal kinematic pair (no backlash) connecting the rotation axis of the servomotor with the axis of the corresponding joint

$$c_m = I_m \dot{\omega}_m + F_m \omega_m + f r_m$$

$$f r = I \dot{\omega} + F \omega + c_l$$

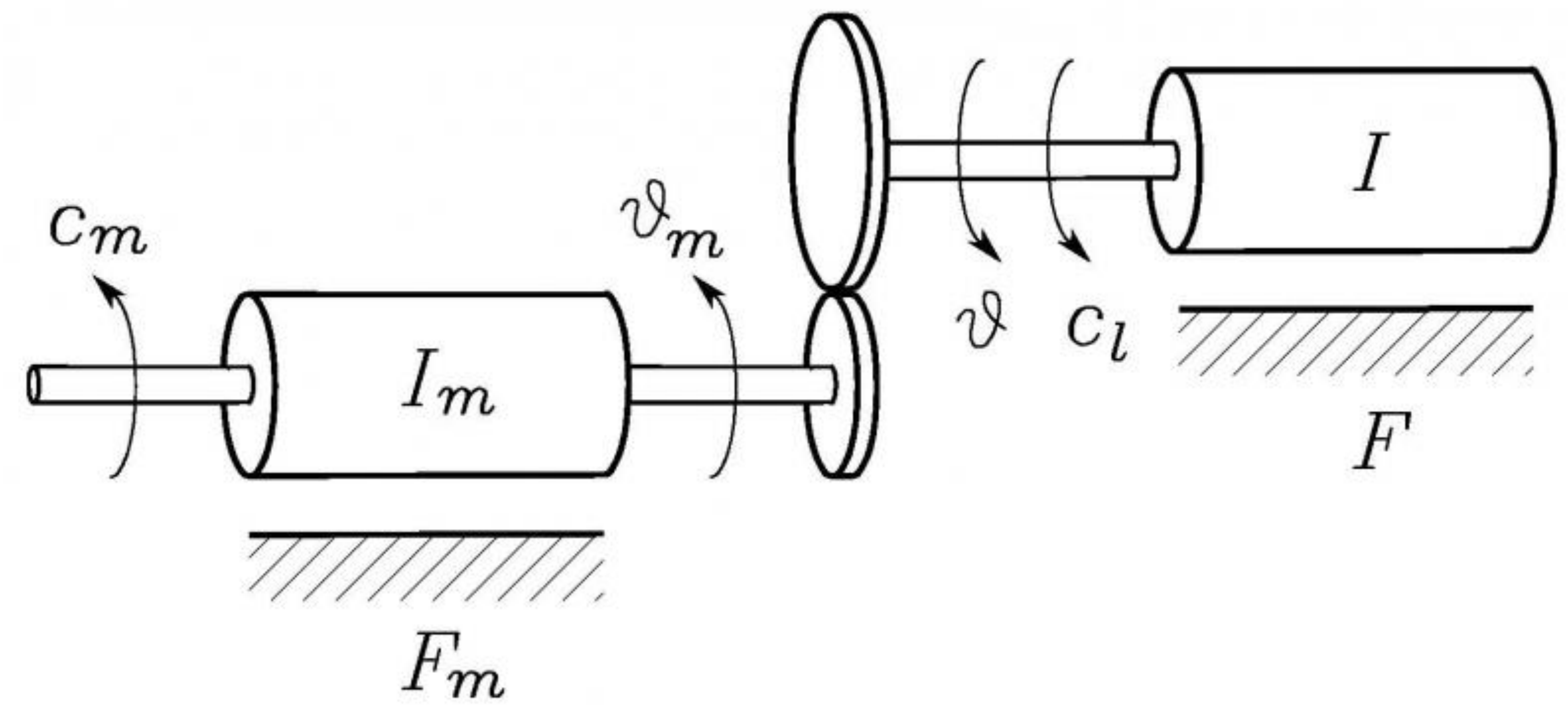
$$\Downarrow \quad k_r = \frac{r}{r_m}$$

$$c_m = I_{eq} \dot{\omega}_m + F_{eq} \omega_m + \frac{c_l}{k_r}$$

$$I_{eq} = \left(I_m + \frac{I}{k_r^2} \right) \qquad F_{eq} = \left(F_m + \frac{F}{k_r^2} \right)$$

$$k_r \gg 1$$

- The inertia moment and the viscous friction coefficient of the load are reflected at the motor axis with a reduction of a factor $1/k_r^2$
- The reaction torque is reduced by a factor $1/k_r$



Schematic representation of a mechanical gear

Example

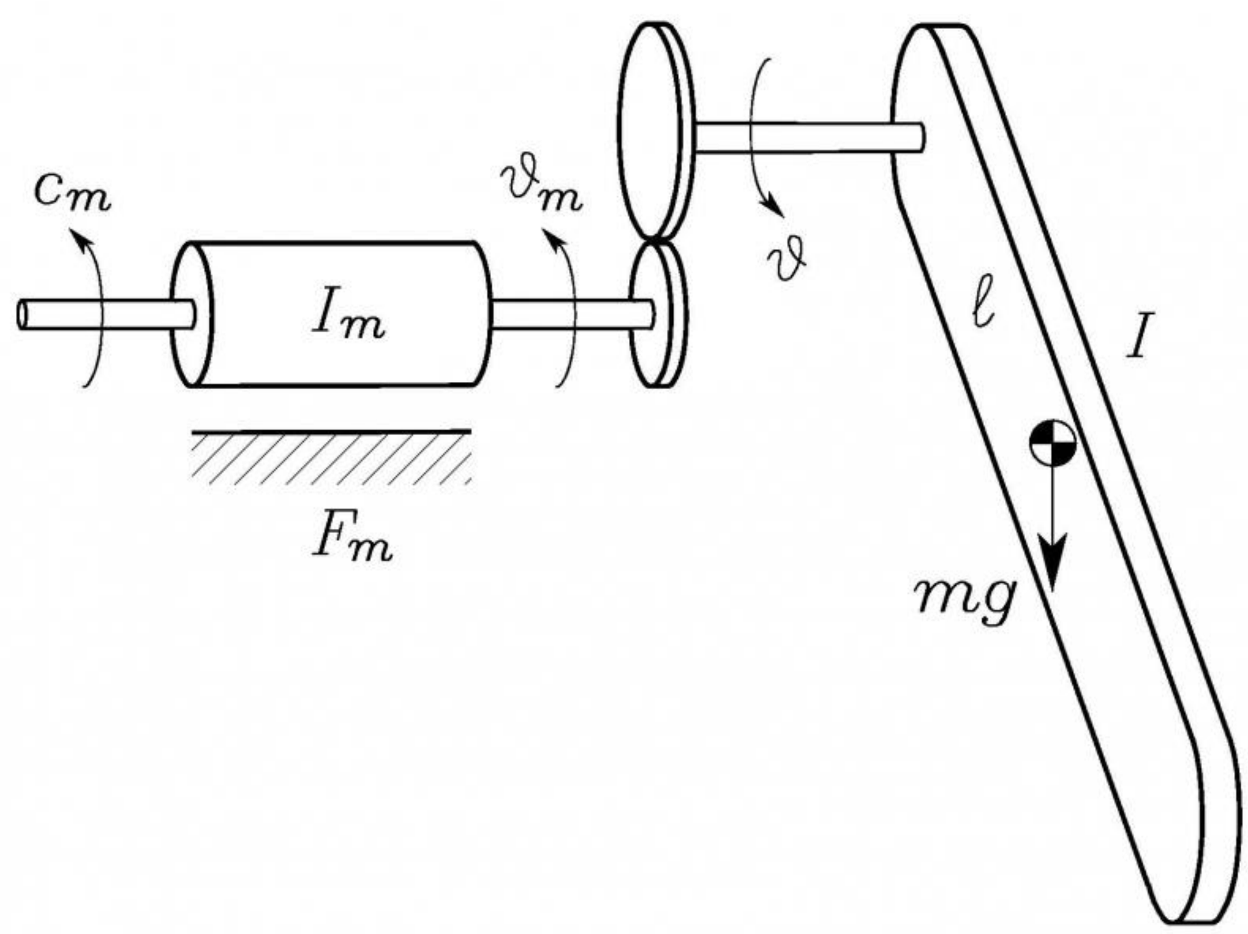
Pendulum actuated via mechanical gear

$$
\begin{aligned}
c_m &= I_m \dot{\omega}_m + F_m \omega_m + f r_m \\
f r &= I \dot{\omega} + F \omega + m g \ell \sin\vartheta
\end{aligned}
$$

$$\Downarrow$$

$$c_m = I_{eq} \dot{\omega}_m + F_{eq} \omega_m + \left(\frac{m g \ell}{k_r} \right) \sin\left(\frac{\vartheta_m}{k_r} \right)$$

- For an N-link manipulator the nonlinear couplings between the motors of the various links will be reduced by the presence of transmissions with large reduction ratios



Pendulum actuated via mechanical gear

Position Control

SECTION 1

Position Control

General scheme of electric drive control

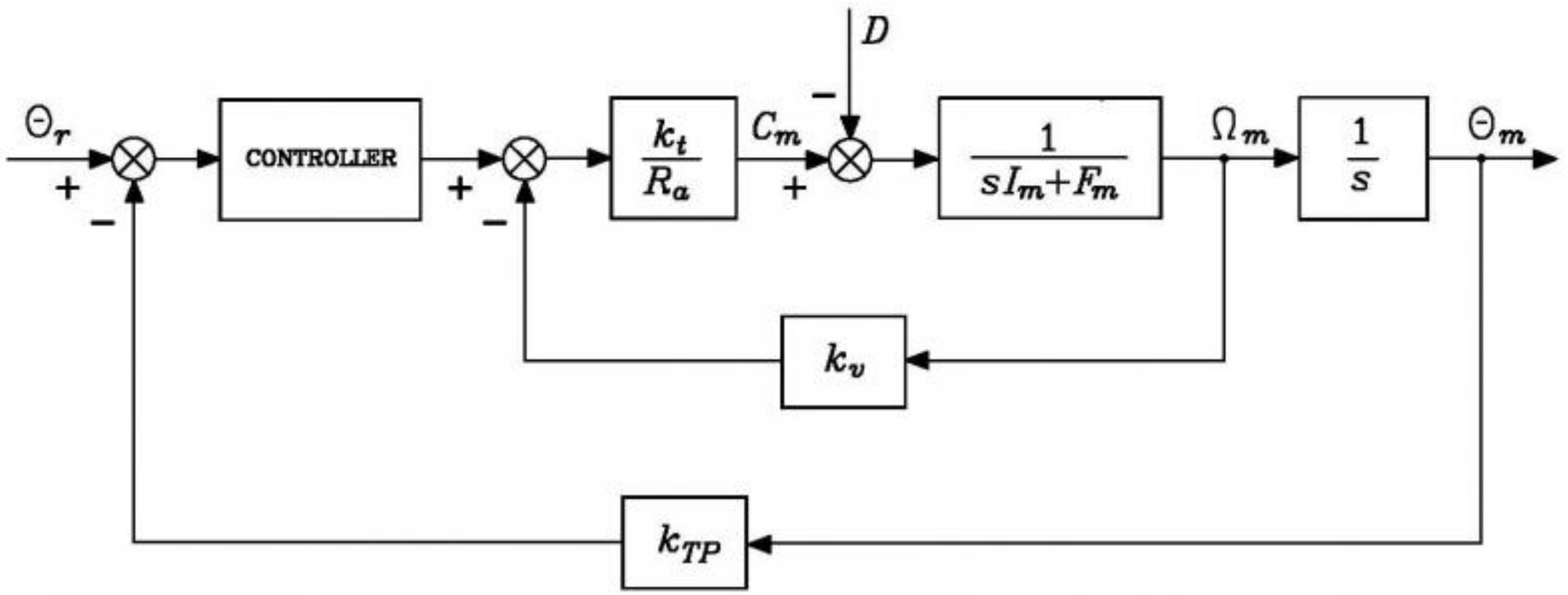
- Velocity-controlled generator

$$\frac{R_a}{k_v k_t} \ll \frac{1}{F_m}$$

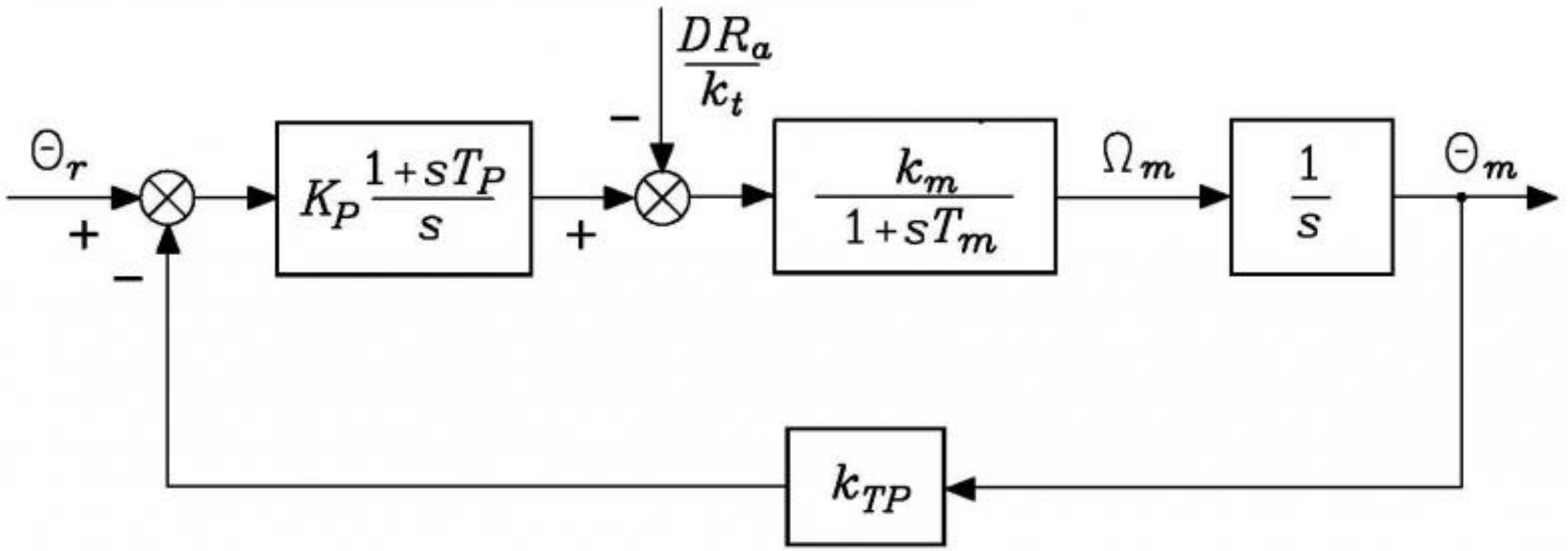
Reduction of disturbance effects on the output $\Longrightarrow$ PI control action

$$k_m = \frac{1}{k_v} \qquad T_m = \frac{R_a I_m}{k_v k_t}$$

- K_P and T_P to be keenly chosen so as to ensure stability of feedback control system and obtain a good dynamic behavior



General block scheme of electric drive control

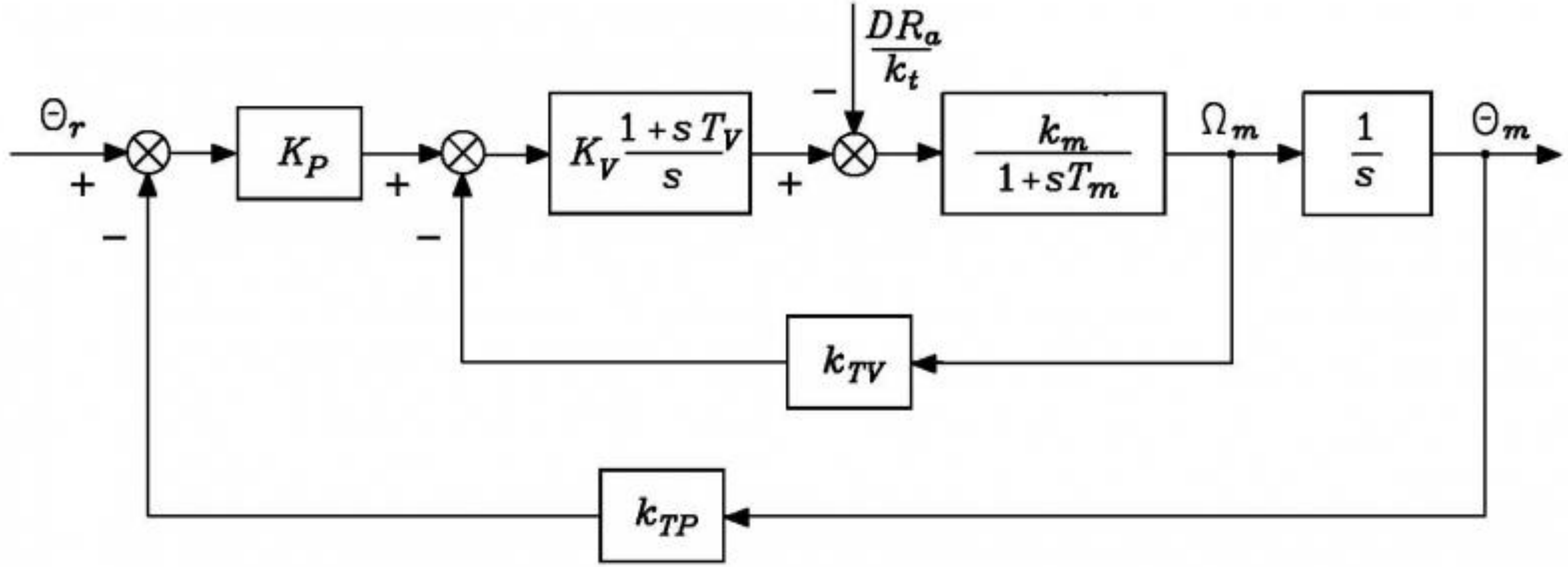


Block scheme of position feedback control

Position and Velocity Feedback

Improvement of transient response $\Longrightarrow$ Include local feedback loop based on angular velocity measurement (tachometer feedback)

- The PI control with parameters K_V and T_V is retained in the internal velocity loop so as to cancel the effects of disturbance on the position ϑ_m at steady state
- The presence of two feedback loops is expected to lead to further reduction of disturbance during transients



Block scheme of position and velocity feedback control

The Motion Control Problem

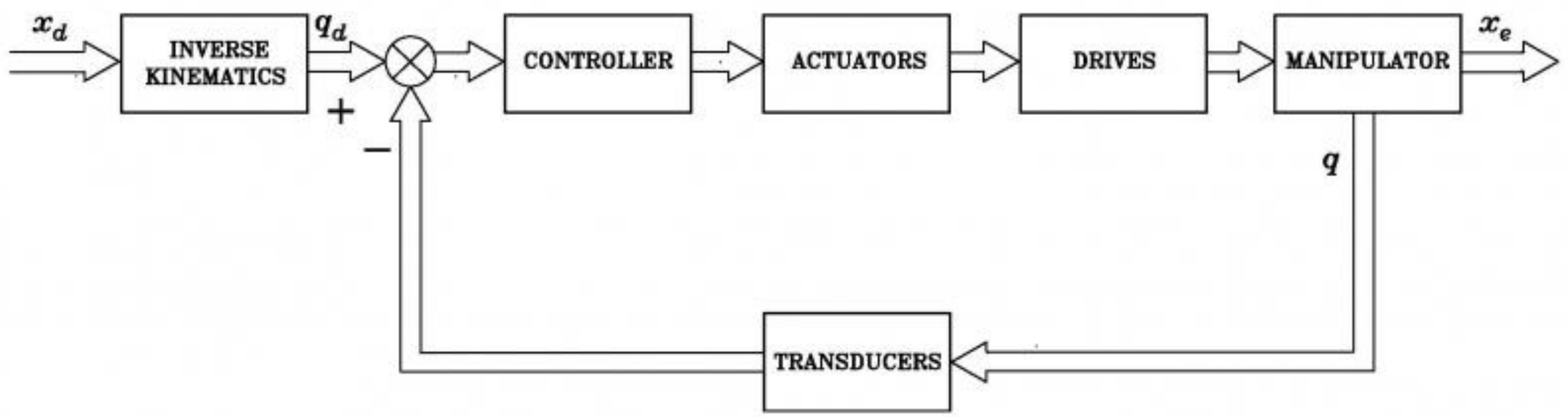
SECTION 1

Joint space control

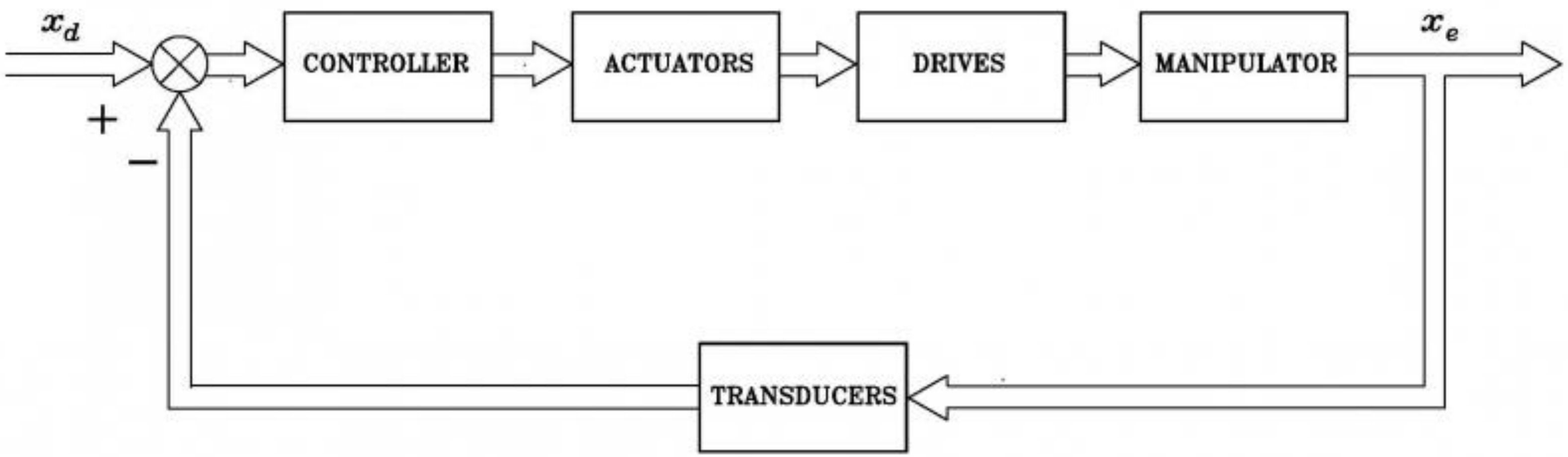
- First stage: inverse kinematics to transform motion requirements from the operational space into the corresponding motion in the joint space
- Second stage: a joint space control scheme is designed to allow tracking of the reference motion
- Operational space variables are controlled open-loop: prone to structure uncertainty (construction tolerance, lack of calibration, gear, backlash, elasticity) or imprecision in the knowledge of the end-effector pose relative to an object to manipulate

Operational space control

- Inverse kinematics embedded in the feedback control loop (greater algorithmic complexity)
- Direct action in the operational space
- Operational space variables typically measured through direct kinematics from measured joint space variables



General scheme of joint space control



General scheme of operational space control

Joint Space Control

SECTION 1

Joint Space Control

- Dynamic model

$$\boldsymbol{B}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{C}(\boldsymbol{q}, \dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{F}_v\dot{\boldsymbol{q}} + \boldsymbol{g}(\boldsymbol{q}) = \boldsymbol{\tau}$$

Control $\equiv$ **Find** $\boldsymbol{\tau}$ **:** $\boldsymbol{q}(t) = \boldsymbol{q}_d(t)$

- Mechanical transmissions $\boldsymbol{K}_r\boldsymbol{q} = \boldsymbol{q}_m$ $\boldsymbol{\tau}_m = \boldsymbol{K}_r^{-1}\boldsymbol{\tau}$

- Electric drives

$$\begin{aligned} \boldsymbol{K}_r^{-1}\boldsymbol{\tau} &= \boldsymbol{K}_t\boldsymbol{i}_a \\ \boldsymbol{v}_a &= \boldsymbol{R}_a\boldsymbol{i}_a + \boldsymbol{K}_v\dot{\boldsymbol{q}}_m \\ \boldsymbol{v}_a &= \boldsymbol{G}_v\boldsymbol{v}_c \end{aligned}$$

Velocity-Controlled Manipulator

- Dynamic model of manipulator and drives

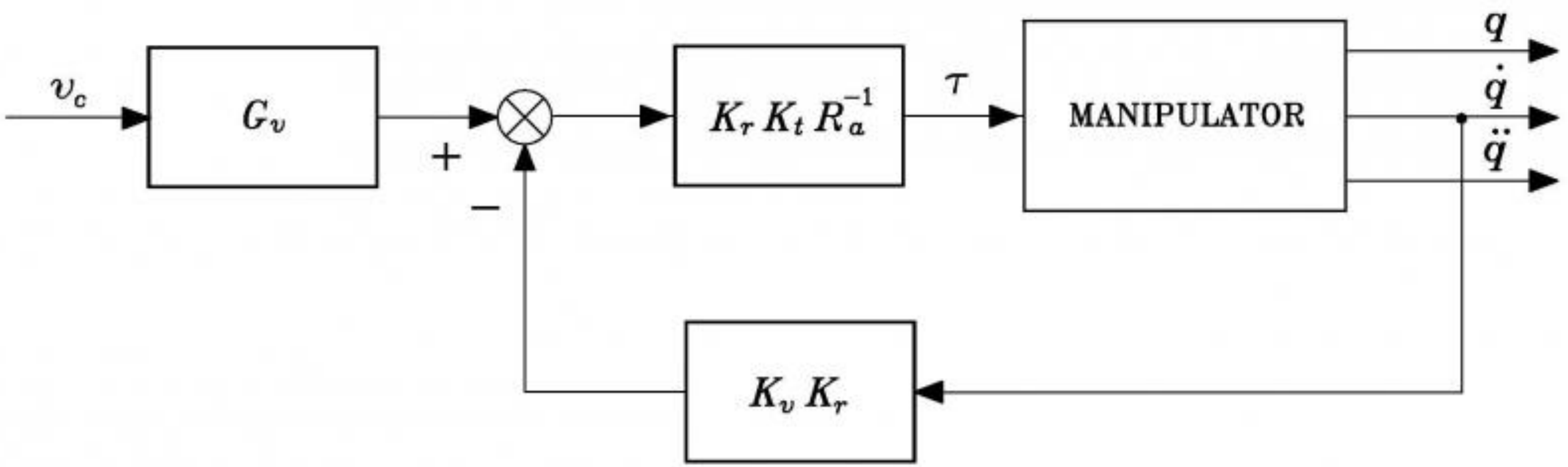
$$B(q)\ddot{q} + C(q,\dot{q})\dot{q} + F\dot{q} + g(q) = u$$
$$F = F_v + K_r K_t R_a^{-1} K_v K_r$$
$$u = K_r K_t R_a^{-1} G_v v_c$$
$$K_r K_t R_a^{-1} G_v v_c = \tau + K_r K_t R_a^{-1} K_v K_r \dot{q}$$
$$\Downarrow$$
$$\tau = K_r K_t R_a^{-1}(G_v v_c - K_v K_r \dot{q}) \gg 1$$

- K_r with elements
- R_a with small elements (high-efficicency servomotors)
- τ not too large

$$\Downarrow$$

- **Decentralized control**

$$G_v v_c \approx K_v K_r \dot{q}$$



Block scheme of the manipulator and drives system as a voltage-controlled system

Torque-Controlled Manipulator

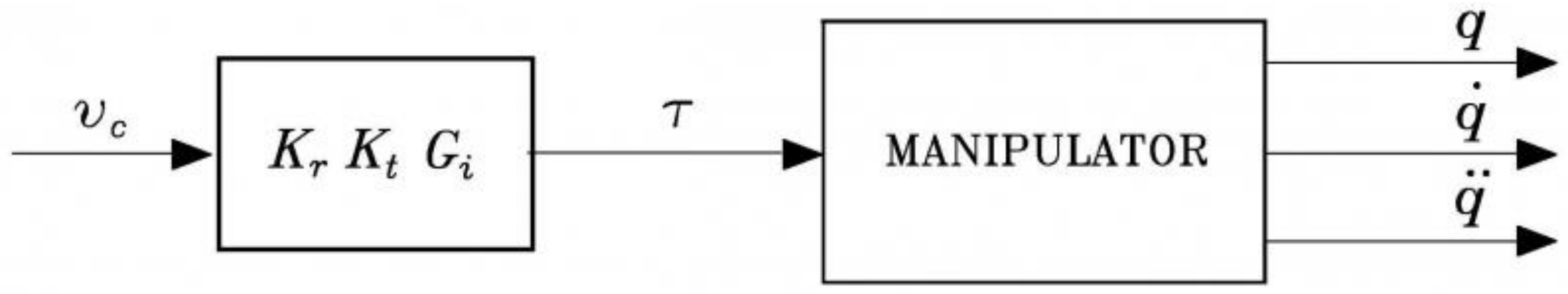
- Reduction of sensitivity to parametric variations of $\boldsymbol{K}_t, \boldsymbol{K}_v, \boldsymbol{R}_a$

$$\boldsymbol{i}_a = \boldsymbol{G}_i \boldsymbol{v}_c$$

$$\Downarrow$$

- **Decentralized control**

$$\boldsymbol{\tau} = \boldsymbol{u} = \boldsymbol{K}_r \boldsymbol{K}_t \boldsymbol{G}_i \boldsymbol{v}_c$$



Block scheme of the manipulator and drives system as a torque-controlled system

Decentralized Control

- Dynamic model at motor side

$$K_r^{-1}B(q)K_r^{-1}\ddot{q}_m + K_r^{-1}C(q,\dot{q})K_r^{-1}\dot{q}_m + K_r^{-1}F_vK_r^{-1} + K_r^{-1}g(q) = \tau_m$$

- Average inertias

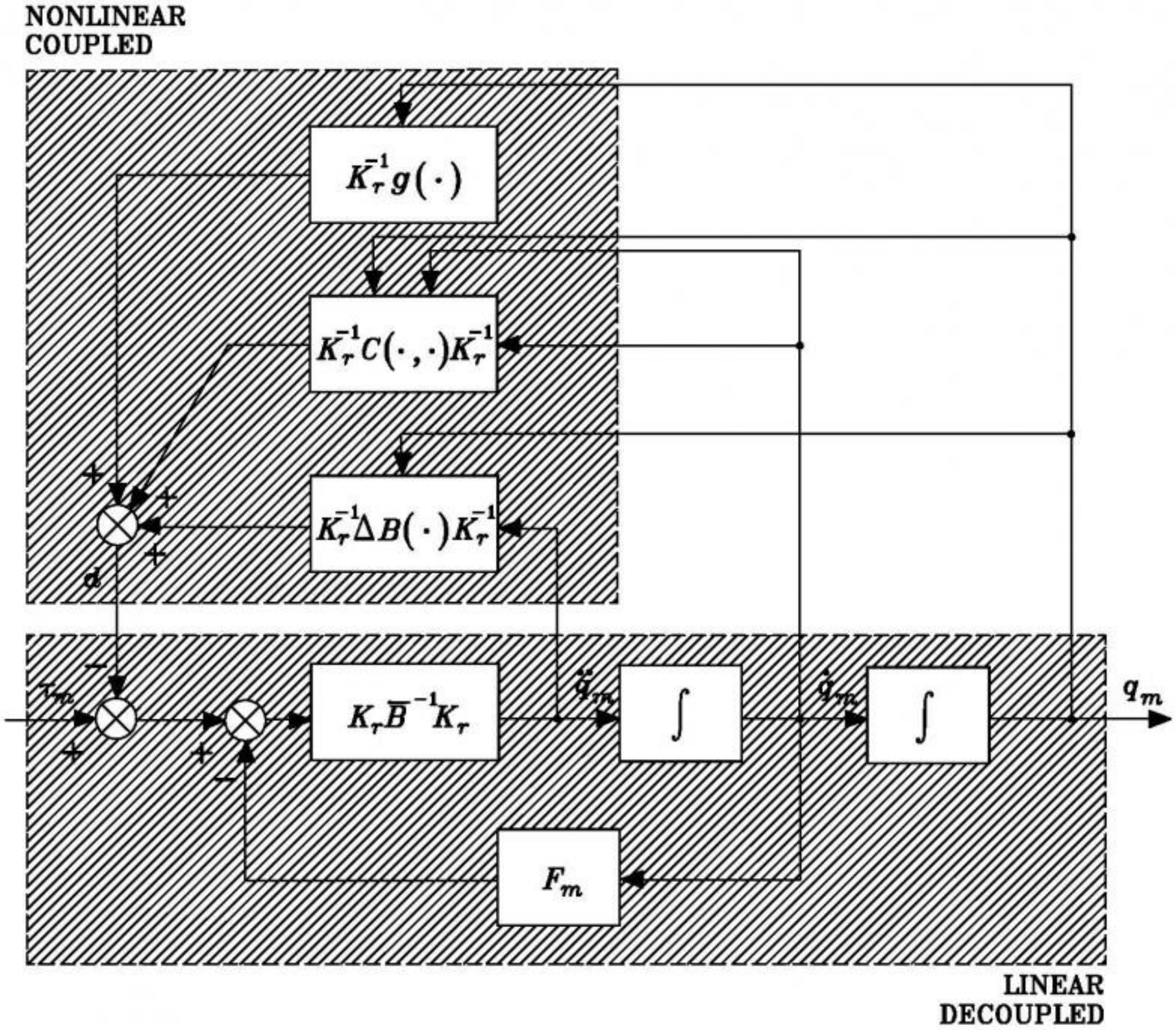
$$B(q) = \bar{B} + \Delta B(q)$$
$$K_r^{-1}\bar{B}K_r^{-1}\ddot{q}_m + F_m\dot{q}_m + d = \tau_m$$

- Viscous friction

$$F_m = K_r^{-1}F_vK_r^{-1}$$

- Disturbance

$$d = K_r^{-1}\Delta B(q)K_r^{-1}\ddot{q}_m + K_r^{-1}C(q,\dot{q})K_r^{-1}\dot{q}_m + K_r^{-1}g(q)$$



NONLINEAR
COUPLED
$K_r^{-1} g(\cdot)$
$K_r^{-1} C(\cdot,\cdot) K_r^{-1}$
$K_r^{-1} \Delta B(\cdot) K_r^{-1}$
d
τ_m
$K_r \overline{B}^{-1} K_r$
$\ddot{q}_m$
$\dot{q}_m$
q_m
F_m
LINEAR
DECOUPLED