Mechatronics, Instrumentation and Design

Invited Talk at:
California State Polytechnic University, Pomona

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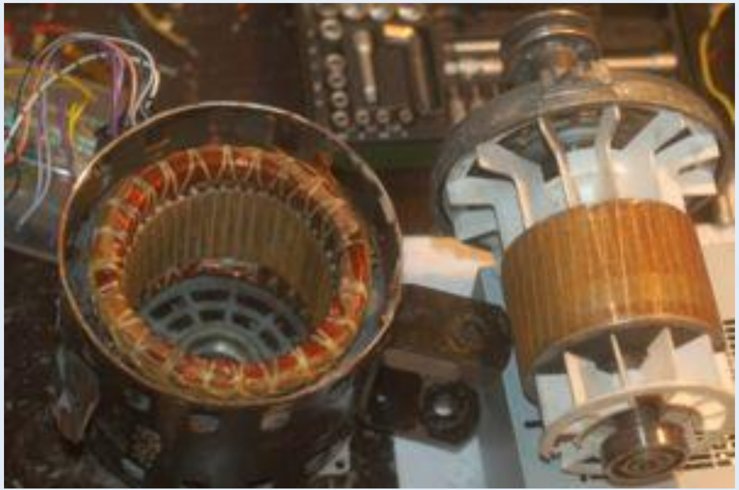
Plan of the Talk

- The Origin of Mechatronics
- Instrumentation, Sensors and Actuators
- Mechatronics and Instrumentation
- Instrumentation and Design
- Illustrative Examples

The Origin of Mechatronics

Yasakawa Electric Co.

- Established in Kitakyushu City, Japan, in 1915
- Main Products: Induction Motors and their Controls (drive unit)
- Global Expansion after World War II
- Many Electromechanical (Mechatronic?) Issues were Encountered



Induction Motor

Advantages

- Cost-effective
- Convenient power source – standard power grid (for single-phase and three-phase ac supply)
- Typically, no commutator and brush mechanisms needed
- No electric spark generation or arcing (no brushes and slip rings) ➔ Less hazardous (e.g., in chemical environments)
- Capability of accurate constant-speed operation without needing servo control
- High capacity, reliability and robustness; easy maintenance; long life

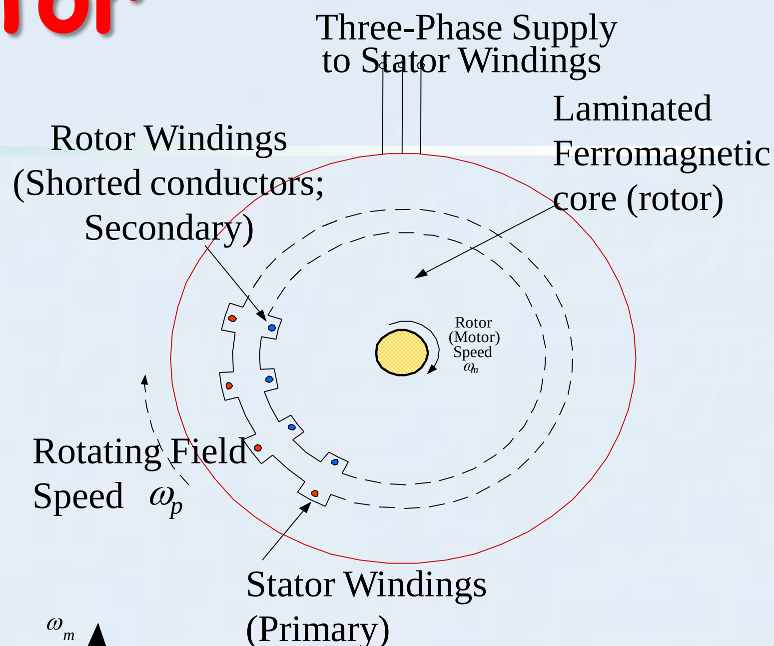
Applications (Including the Current Applications)

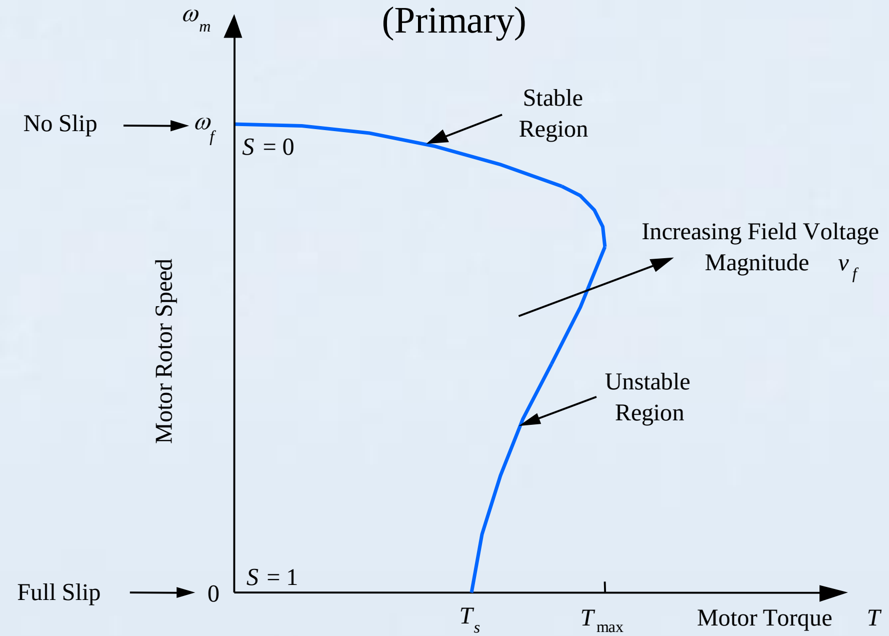
- **Heavy-duty:** Rolling mills, presses, elevators, cranes, material handlers
- **Continuous Motion:** Conveyors, mixers, extruders, pulping machines
- **Household and Industrial:** Refrigerators, pumps, compressors, fans

Main Principle: Generation of a rotating magnetic field

Induction Motor

- **An AC Motor**
- **Early Control (Yasakawa): Primitive, Two-speed, Pole-Changing Control**
- **Modern Control: Variable-speed, Frequency Control and Field Vector (Magnetic Flux Vector) Control**





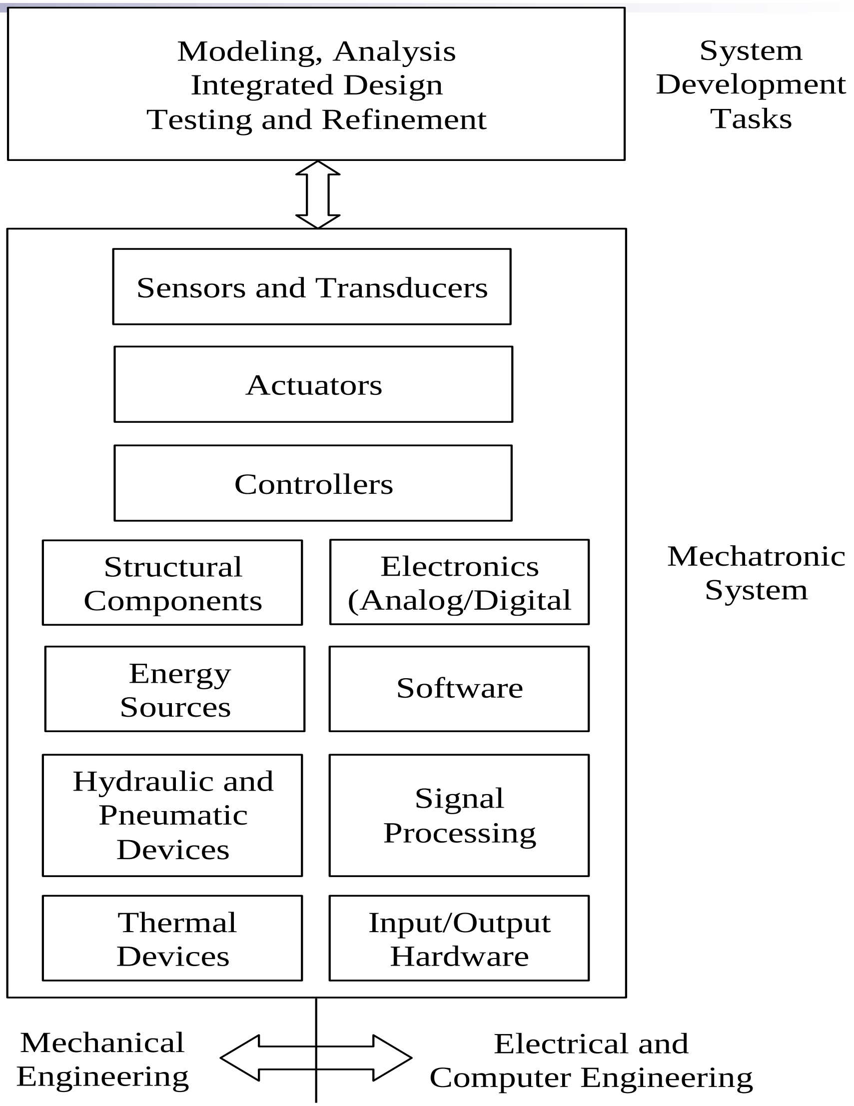
Challenges Faced by Yasakawa

- **Even though, pole changing control was adequate for constant speed operations, much better control is needed for variable-speed operation**
- **Operation has to be in the "stable" region of the motor**
- **Both "electrical" and "mechanical" considerations of the motor required equal attention**

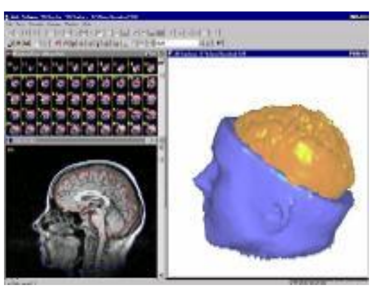
***Note*: All these are motivations for a "Mechatronic" approach for the problem**

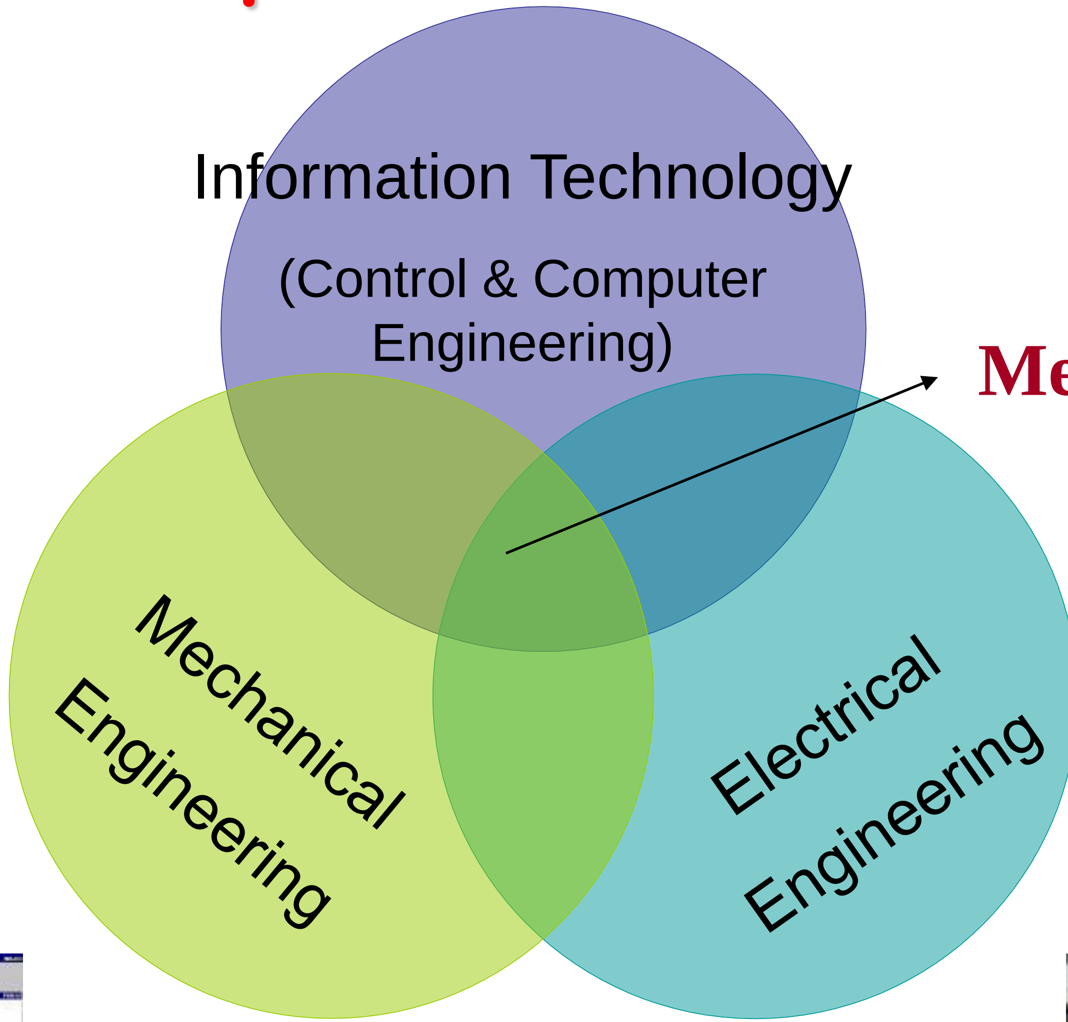
The Origin of the Term

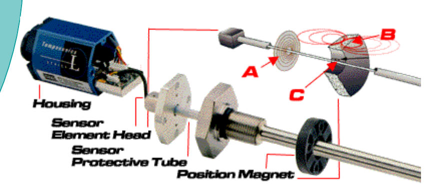
- By Fusing: "MECHAnics and elecTRONICS," in 1969
- Yasakawa Electric Co. Registered a Trademark in 1972

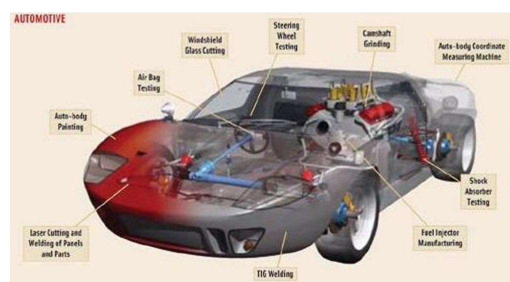


Traditional Representation of Mechatronics









Instrumentation, Sensors and Actuators

Commercial Sensors

Motion Sensors: Potentiometer, differential transformer (LVDT), magnetostrictive (temposonic) displacement sensor, magnetic induction proximity sensor, tachometer, resolver, synchro, gyro, piezoelectric accelerometer, laser ranger, ultrasound ranger

Force/Torque Sensors: Semiconductor strain gauge, motor current sensor

Fluid Flow Sensors: Coriolis velocity meter, pitot (pee-toh) tube, rotameter, orifice flow meter

Pressure Sensors: Manometer, Bourdon tube, diaphragm type

Temperature Sensors: Thermocouple, thermistor, resistance temperature detector (RTD)

Note: Pressure and flow are correlated →pressure sensing can be used for flow sensing

Instrumentation

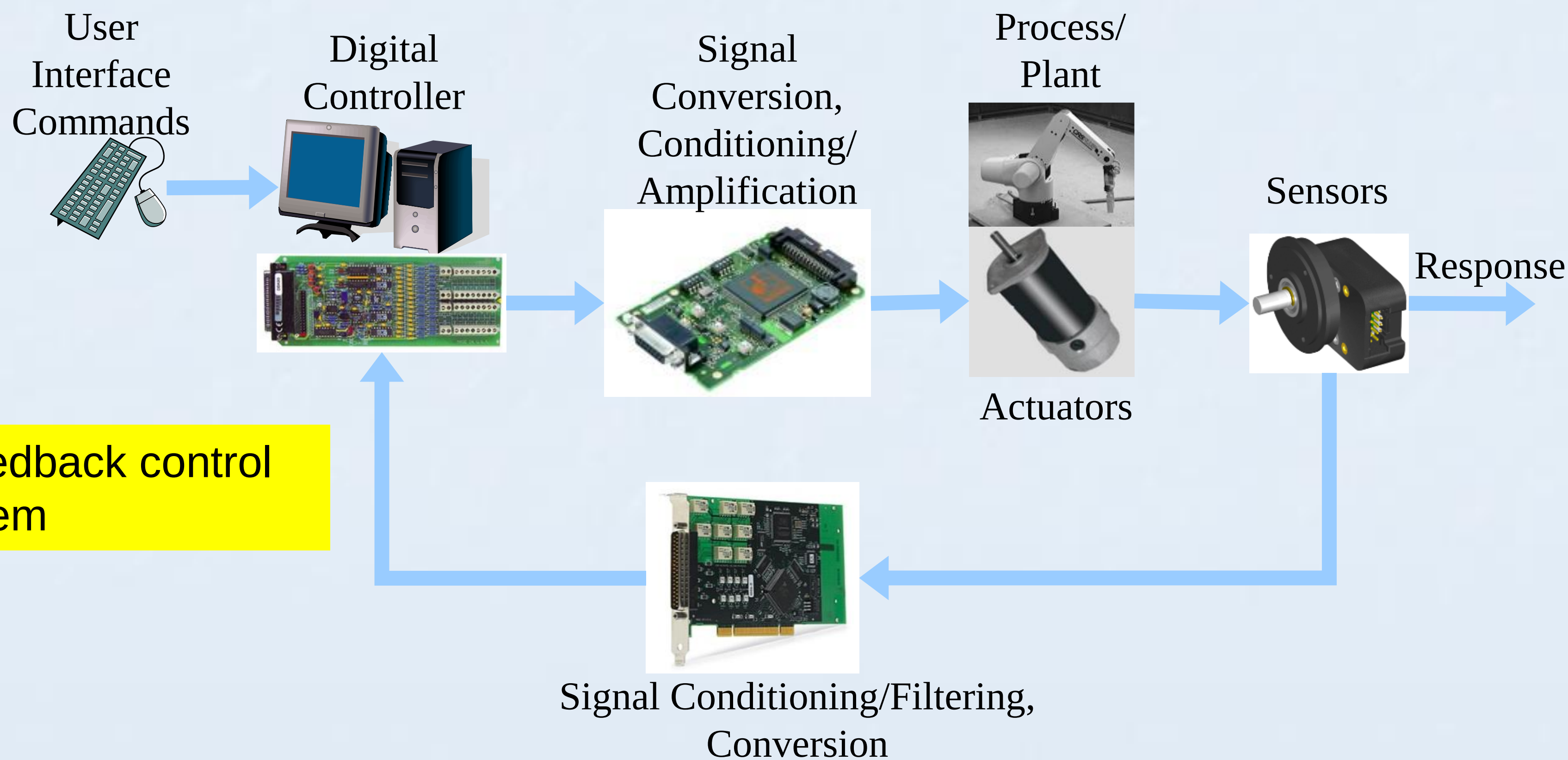
- Identify components for "instrumenting" a system **(consider: type, functions, operation, interaction, etc.)**
- Address component interfacing **(interconnection)**
- Decide parameter values **(component sizing, system tuning, accuracy, etc.)** to meet performance requirements **(specifications)**

Typically, the instruments (devices) are commercially available (a finite set)

Applications: **Processing; production; motion; monitoring; testing and qualification; product quality assessment; fault prediction, detection and diagnosis; warning generation; surveillance; model identification; control (direct, supervisory, etc.)**

Components of Instrumentation

- Sensors and Transducers
- Actuators (including Control Actuators)
- Controllers
- Signal Conditioning/Conversion/Modification Devices
- Power Supplies
- Protection Devices



A feedback control system

Sensors

What are variables?
What are parameters?

- **Sensor:** Measures (senses) unknown signals and parameters of a plant and its environment

  (Sensors are needed to monitor and "learn" about the system)

What categories of things may be sensed in our context?

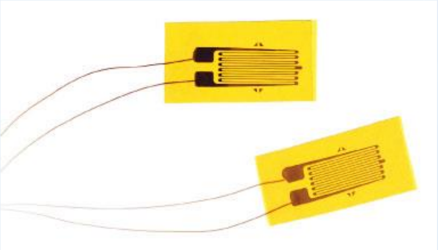
- **Useful in:** Process monitoring; testing and qualification; product quality assessment; fault prediction, detection and diagnosis; warning generation; surveillance; model identification; control; general operation of a system
- **Sensor System:** May mean, 1. Multiple sensors, sensor/data fusion (one sensor may not be adequate for the particular application) **or,** 2. Sensor and its accessories (signal processing, data acquisition, display, etc.)

Sensor Examples

Potentiometers

Piezoelectric Accelerometers

Resolvers



Strain Gauges

LVDTs

Thermocouples

Which of these are you familiar with?

Tachometers

Servovalves

Actuators

Stepper Motor

- **Needed to "drive" a plant**

Examples: Stepper motors, solenoids, dc motors, hydraulic rams, pumps, pneumatic actuators, valves, relays, switches, heaters/cooler

Why are these actuators?

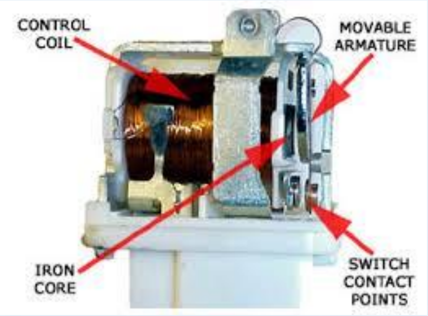
Control Actuators: Perform control actions; they drive control devices. (e.g., control valves)

Solenoid Valve Actuators

Eccentric DC Motor

Rotary Hydraulic Actuator

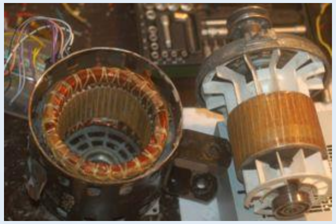
Hydraulic Ram



Relay

What is a relay?

Which of these are you familiar with?



AC Motor

DC Motor

Mechanical Components

Mechanical Sensors:

- **Springs (displacement measures force)**
- **Mechanical limit switches**
  (contact indicates position limit)
- **Indentation type hardness sensors**
  (size of surface indentation → hardness)
- **Pendulum-based mass/inertia sensors**
  (period of oscillation → inertia)
- **Mechanical flow meters**
  (count rotations over a time period)

Advantages and disadvantages of mechanical components compared to electronic components?

- Load bearing/structural components (strength and surface properties)
  (Bearings, springs, shafts, beams, columns, flanges)
- Fasteners (strength)
  (Bolts and nuts, locks and keys, screws, rivets, and spring retainers, welding, bracing, soldering)
- Dynamic isolation components (transmissibility)
  (Springs, dampers, shock and vibration mounts, inertia blocks, suspension systems)
- Transmission components (motion conversion)
  (Gears, friction or traction drives, lead screws and nuts, power screws, racks and pinions, cams and followers, chains and sprockets, belts and pulleys or drums, differentials, kinematic linkages, flexible couplings, fluid transmissions)
- Mechanical actuators (force/torque generation)
  (Hydraulic pistons and cylinders or rams, hydraulic motors, their pneumatic counterparts)
- Mechanical controllers (control of energy dissipation)
  (Clutches, brakes, hydraulic and pneumatic servo valves)

Example 1

Ear cleaning using a cotton swab:

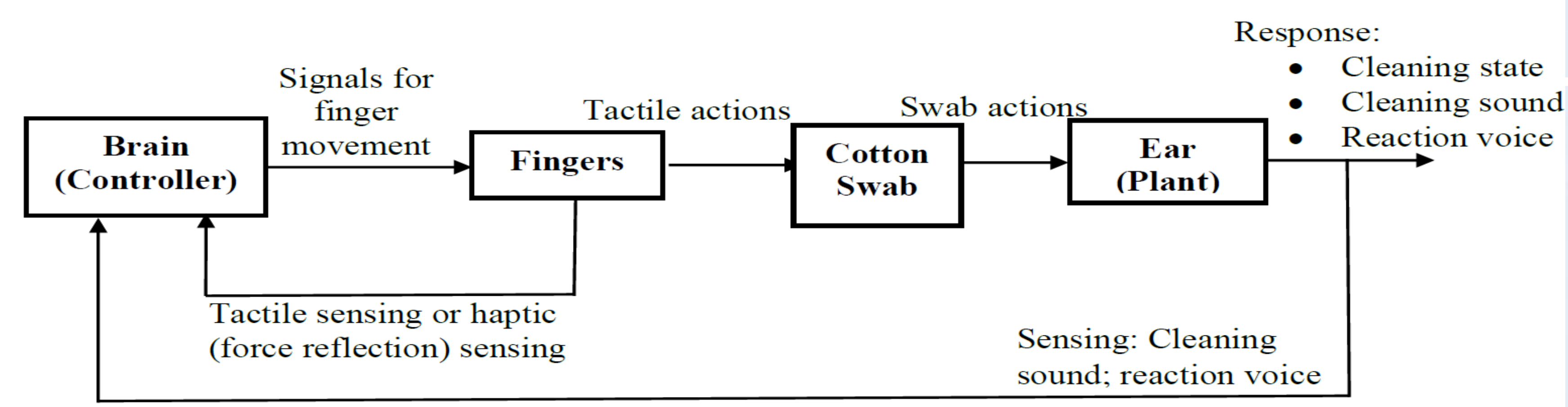
- Self-cleaning
- Cleaning by another person

Questions:

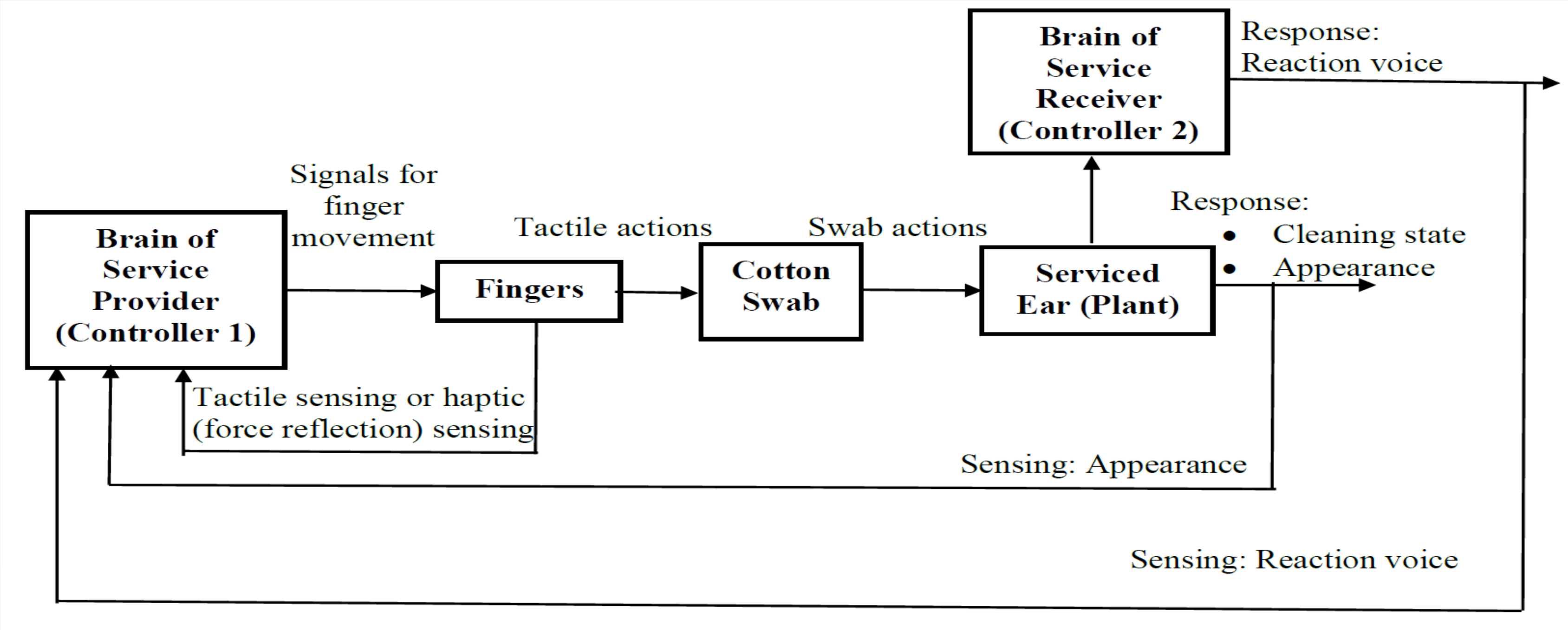
- What are sensors, actuators, and controllers?
- How are they interacting?

Example 1 (Cont'd)

Case 1: Only one controller (brain of self-cleaner)



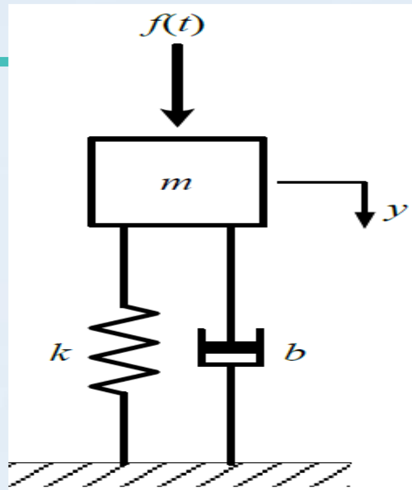
Case 2: Two controllers (brains of service provider and service receiver)

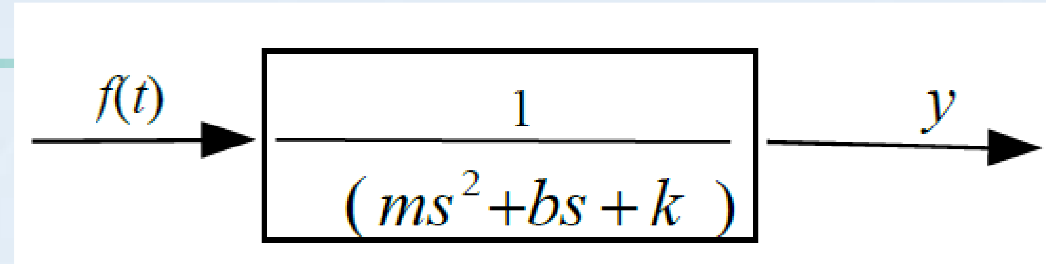


Example 2

Spring and Damper as Natural/Passive (Implicit) Sensors

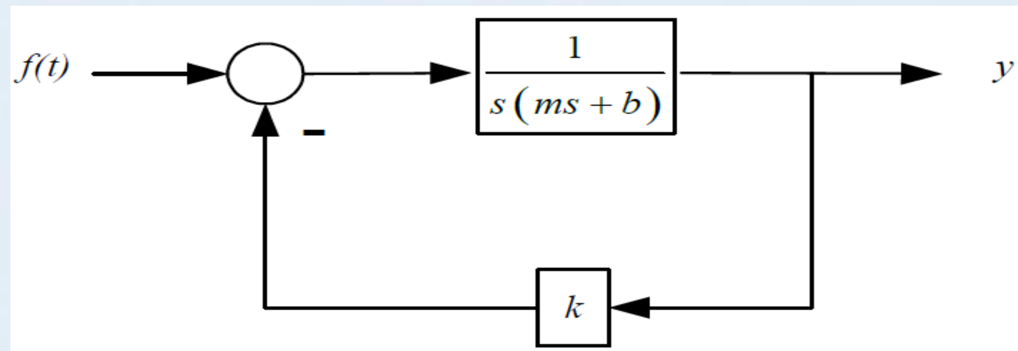
Mechanical Oscillator:



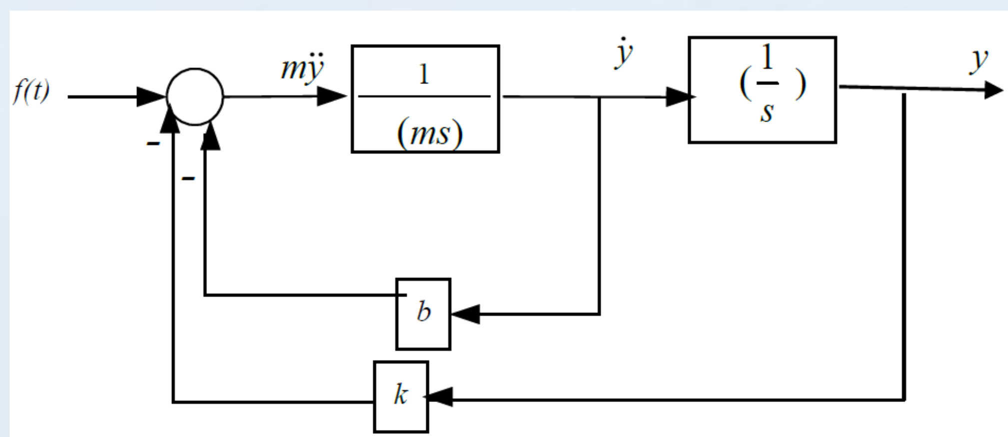


Open loop (no sensory feedback). Plant = entire mass-spring-damper unit.

Displacement/Force feedback (natural displacement/force sensor: spring). Plant = mass + damper

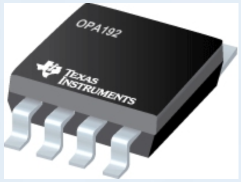


Force/speed feedback (natural sensors: spring and damper for displacement/ force and speed/force sensing). Plant = mass.



Other Components

- **Controller:** **Generates control signals according to which the plant (and control devices) are driven**
- **Signal Conditioning/Conversion Devices**
  - **Filters:** **Low-pass, high-pass, band-pass, notch, tracking**
  - **Amplifiers:** **Charge amps, power amps, voltage amps, power amps (all use op amps)**
  - **Modulators/Demodulators**
  - **Voltage-Current-Frequency Converters**
  - **ADC, DAC, Data Acquisition (DAQ) Boards**
- **Power Supplies**
- **Protection Devices**



Op Amp

Instrumentation Filter/Amp

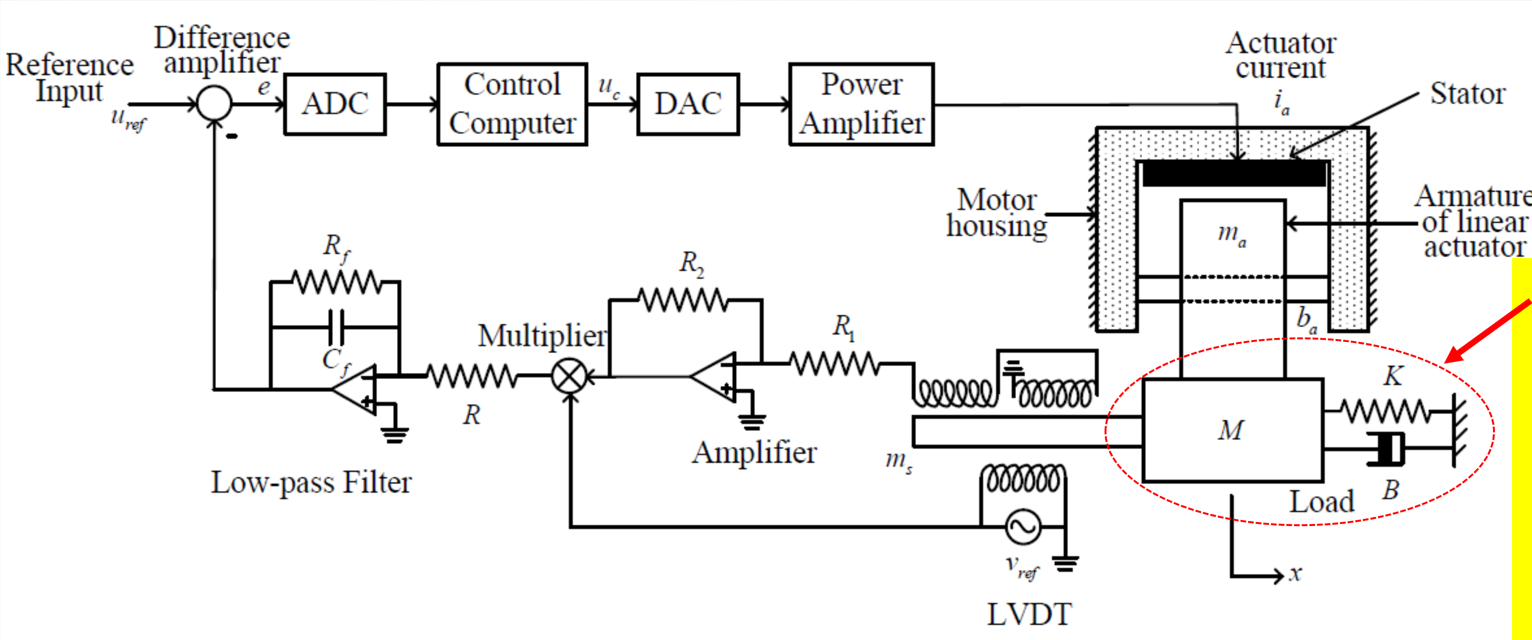
DAQ Board

Which are "signal conditioning," which are "signal conversion," which are signal modification?

Discussion Topic

In “Instrumentation” why is it not enough to just learn everything about sensors and actuators?

Illustrative Example: A Plant Driven by a Linear Actuator



May have to be designed (continuous)

Other "instruments" are commercially available

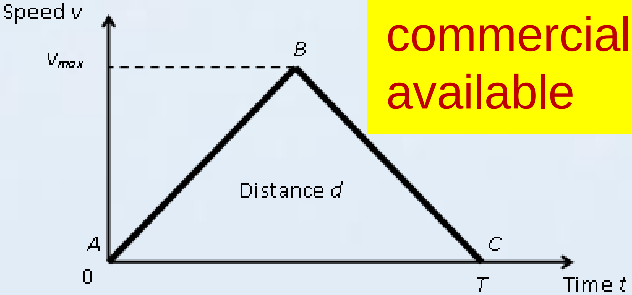
$M = 1.0$ kg, $m_s = 0.01$ kg

$B = 20$N/m/s, $K = 2500.0$ N/m, $d = 0.02$ m, $T = 1.0$ s

LVDT voltage amplifier gain = 10.0;

Low-pass filter gain = 1.0;

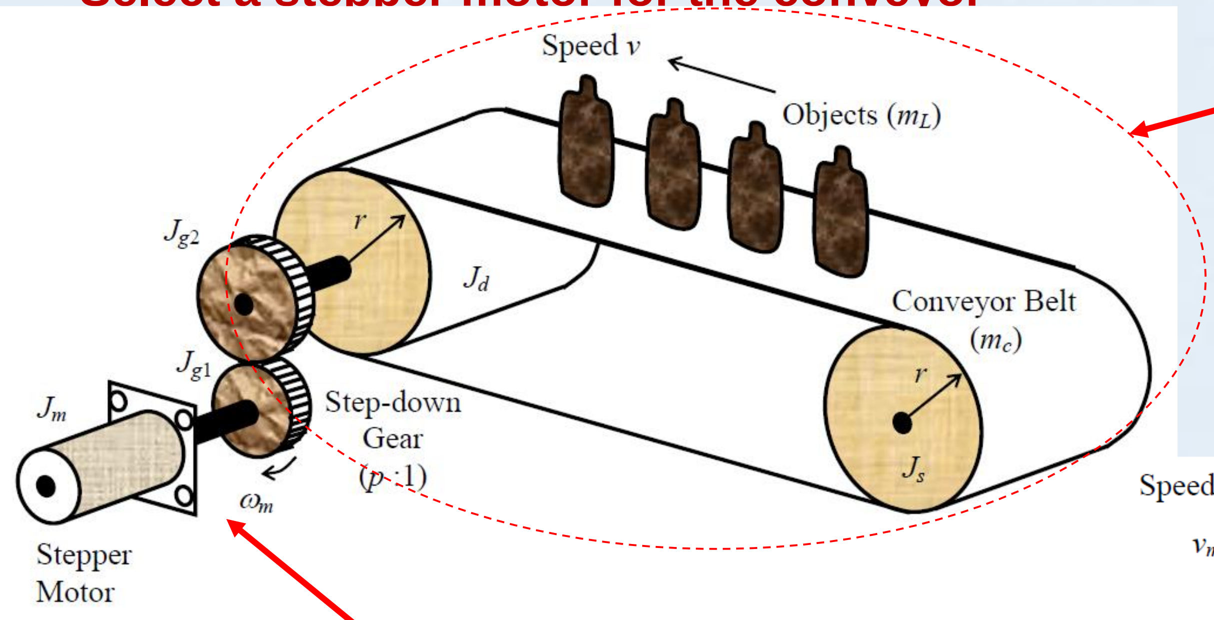
$R_1 = 1.0$ kΩ; $R = 10.0$ kΩ



Note: T = intermittent motion period

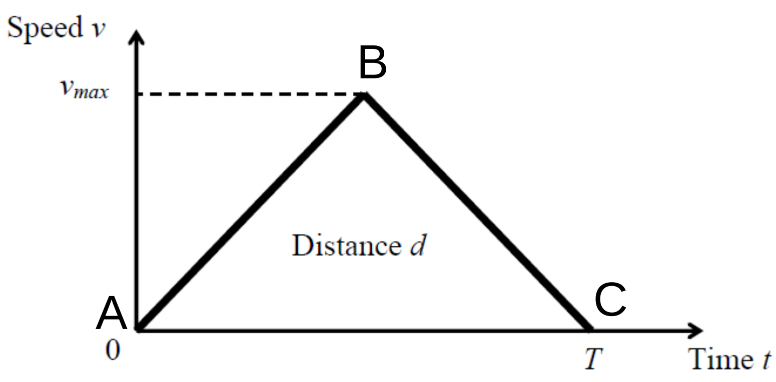
Illustrative Example: Product Conveyor

- Industrial conveyor for product completion, inspection, movement
- Conveyor moves intermittently at a fixed rate ➔ indexes objects through distance *d* in time period *T*
- A triangular speed profile is used for each motion interval, with equal acceleration and a deceleration
- A gear unit with step-down speed ratio *p*:1, *p* > 1, may be used if necessary
- Select a stepper motor for the conveyor



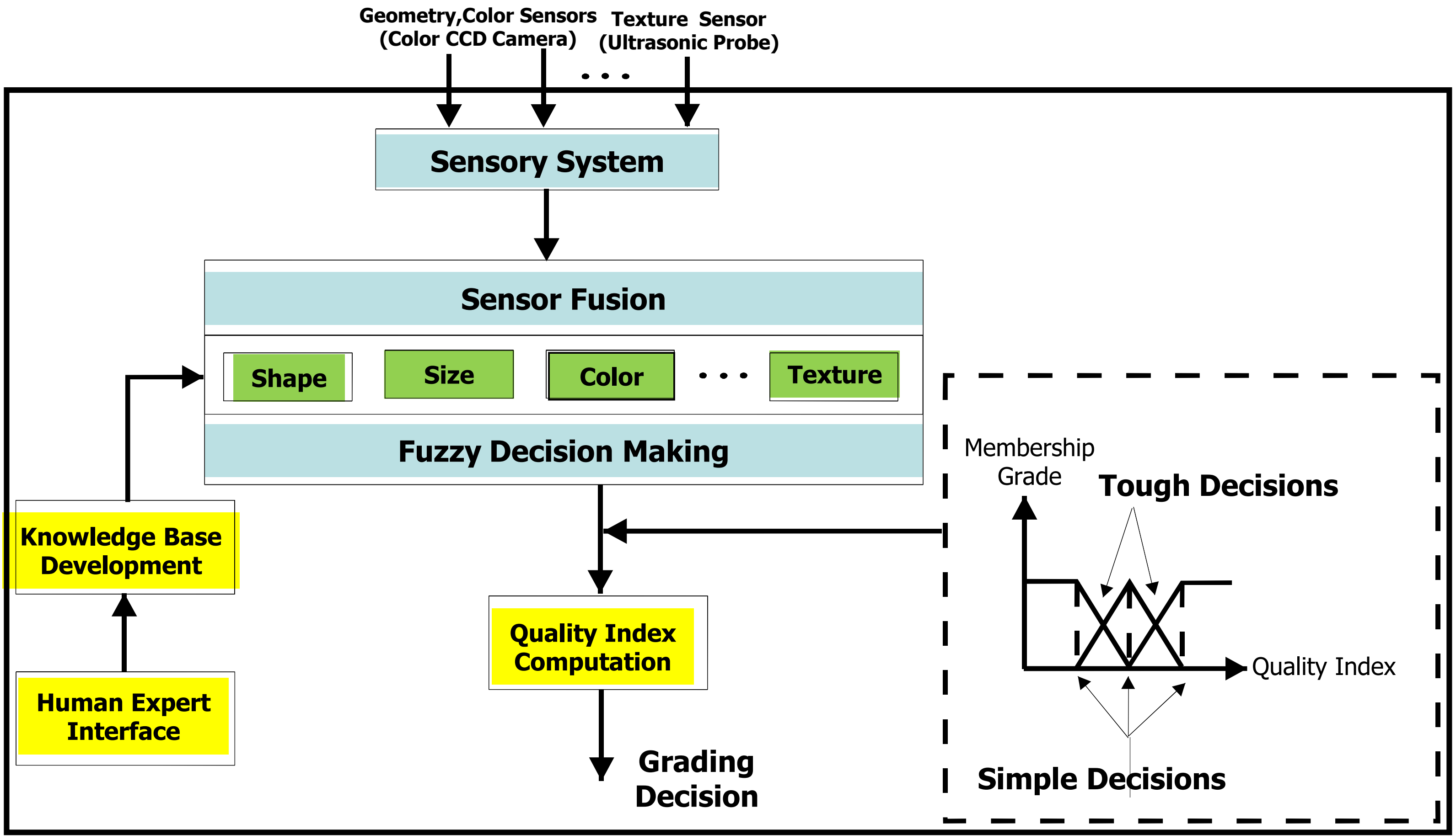
May have to be designed (continuous)

Commercially available "instruments" (motor, gear)



Intelligent Herring-Roe Grader

Architecture of the Grading System



Operation of the Roe Grading Machine

Questions on the Herring Roe Grader

- **What are the sensors?**
- **What are the actuators?**
- **What are other key hardware?**
- **What other types of sensor may be used to replace the exiting ones or to improve performance? Why?**
- **What other types of actuators may be used to replace the exiting ones or to improve performance? Why?**

Application Scenarios of Sensors, Actuators, and Mechatronics

Applicable Engineering Fields

Aeronautical and Aerospace Engineering: Aircraft, spacecraft

Civil Engineering: Monitoring of civil engineering structures (bridges, buildings, etc.)

Chemical Engineering: Monitoring and control of chemical processes and plants

Electrical and Computer Engineering: Development of electronic hardware and computer-integrated devices, hard drives, etc.; control and monitoring of electrical and computer systems

Materials Engineering: Material synthesis processes

Mechanical Engineering: Monitoring and control of vehicles and transit systems, robots, manufacturing plants, industrial plants, jet engines, thermo-fluid systems, etc.

Mining and Mineral Engineering: Mining machinery and processes

Nuclear Engineering: Nuclear reactors; testing and qualification of components

Add other examples to each field

Automobile Sensors

Powertrain (Engine & Transmission) →

- Air flow
- Air-fuel ratio
- Camshaft motion
- Coolant fluid level
- Crankshaft motion
- Detonation
- Exhaust Oxygen
- Manifold pressure
- Oil level
- Oil temperature
- Throttle position
- Transmission output speed
- Transmission temperature

In each situation, how is the sensed information used?

What is the best sensor for a task? You should be able to answer at the end of the course

Driving Aid →

- Accelerator position
- Antilock braking (ABS)
- Cameras
- Radar/Ultrasonic/ Infrared (parking, object detection)
- Steering rate
- Tactile (haptic-touch)
- Vehicle speed

Develop another example of sensor use, in this format

Safety and Comfort →

- Brake fluid
- Compartment temperature/humidity
- Door position
- Electronics monitoring and diagnosis
- Outside conditions
- Ride comfort (acceleration for active suspension control)
- Tire pressure
- Washer fluid level

Automobile Actuators

Powertrain (Engine & Transmission) →

- Brushless dc motors
- Fluid pumps and blowers
- Linear actuators for valves
- Lubrication oil pumps
- Transmission actuators
- Stepper motors for cooling fans
- Throttle valve actuators

Select one scenario (e.g., active suspension). Draw a schematic diagram to show how sensor, actuator, and controller are interconnected and operated to achieve the objective

Driving Aid →

- Automated action devices
- Antilock braking system (ABS) actuators
- Cruise control actuators
- Electric parking brakes
- Headlight movement actuators
- Piezoelectric actuators
- Solenoids
- Switches and relays
- Torque motors

Develop another example of actuator use, in this format

What is the best actuator for a task? You should be able to answer at the end of the course

Safety and Comfort →

- Active suspension actuators (e.g., hydraulic)
- Heating-ventilation-air conditioning (HVAC) actuators
- Stepper motors
- Sunroof movement actuators
- Windshield wiper actuators
- Window movement actuators

Sensors and Actuators in Engineering Applications

Why is a “heat source” considered as an “actuator”?

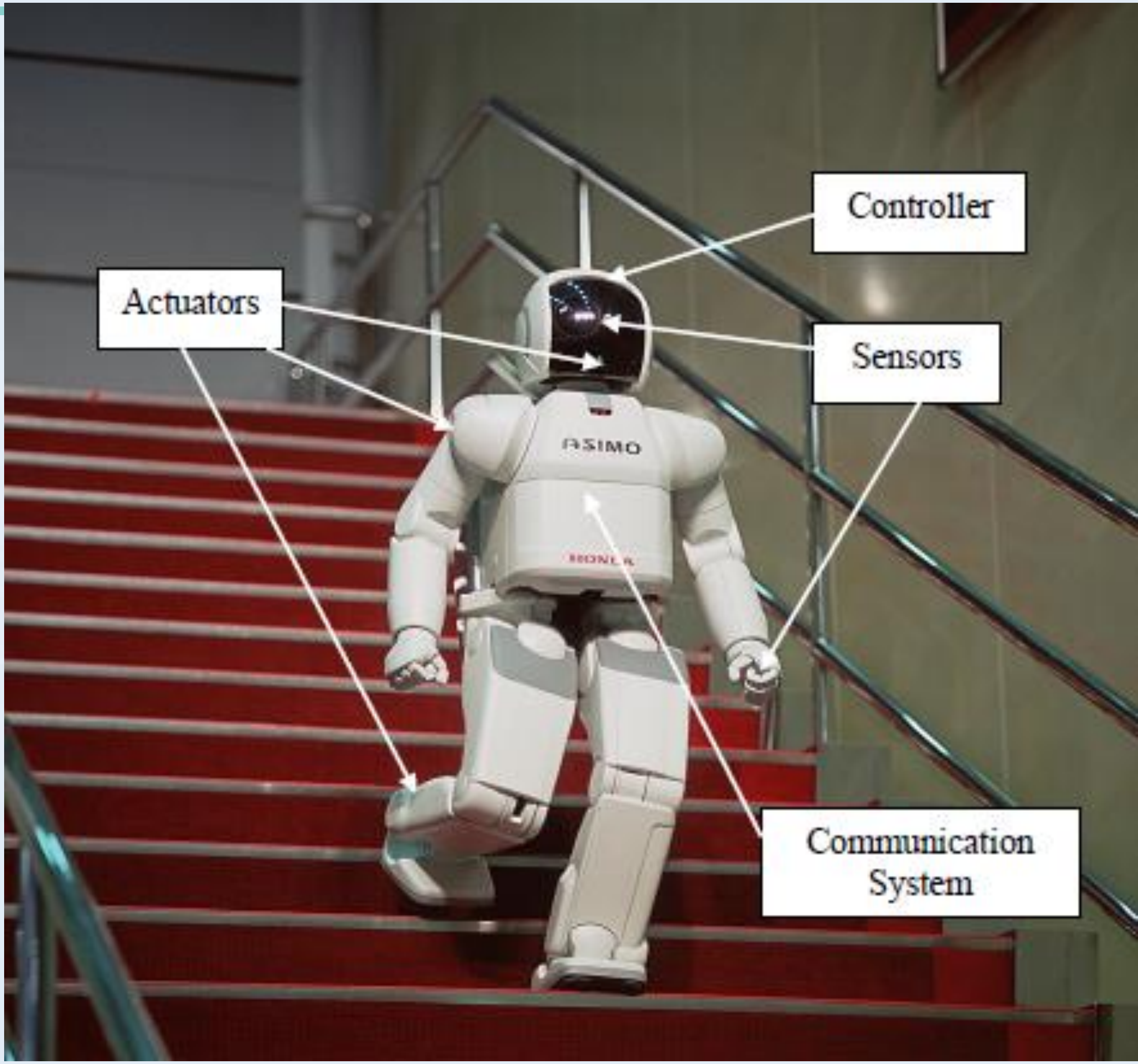
Process	Typical Sensors	Typical Actuators
Aircraft	Displacement, speed, acceleration, elevation, heading, force pressure, temperature, fluid flow, voltage, current, global positioning system (GPS)	DC motors, stepper motors, relays, valve actuators, pumps, heat sources, jet engines
Automobile	Displacement, speed, force, pressure, temperature, fluid flow, fluid level, vision, voltage, current, GPS, radar, sonar	DC motors, stepper motors, valve actuators, linear actuators, pumps, heat sources
Home Heating System	Temperature, pressure, fluid flow	Motors, pumps, heat sources
Milling Machine	Displacement, speed, force, acoustics, temperature, voltage, current	DC motors, ac motors
Robot	Optical image, displacement, speed, force, torque, tactile, laser, ultrasound, voltage, current	DC motors, stepper motors, ac motors, hydraulic actuators, pneumatic actuators
Wood Drying Kiln	Temperature, relative humidity, moisture content, air flow	AC motors, dc motors, pumps, heat sources

High-Speed Ground Transit: Is This a "Mechatronic" System?

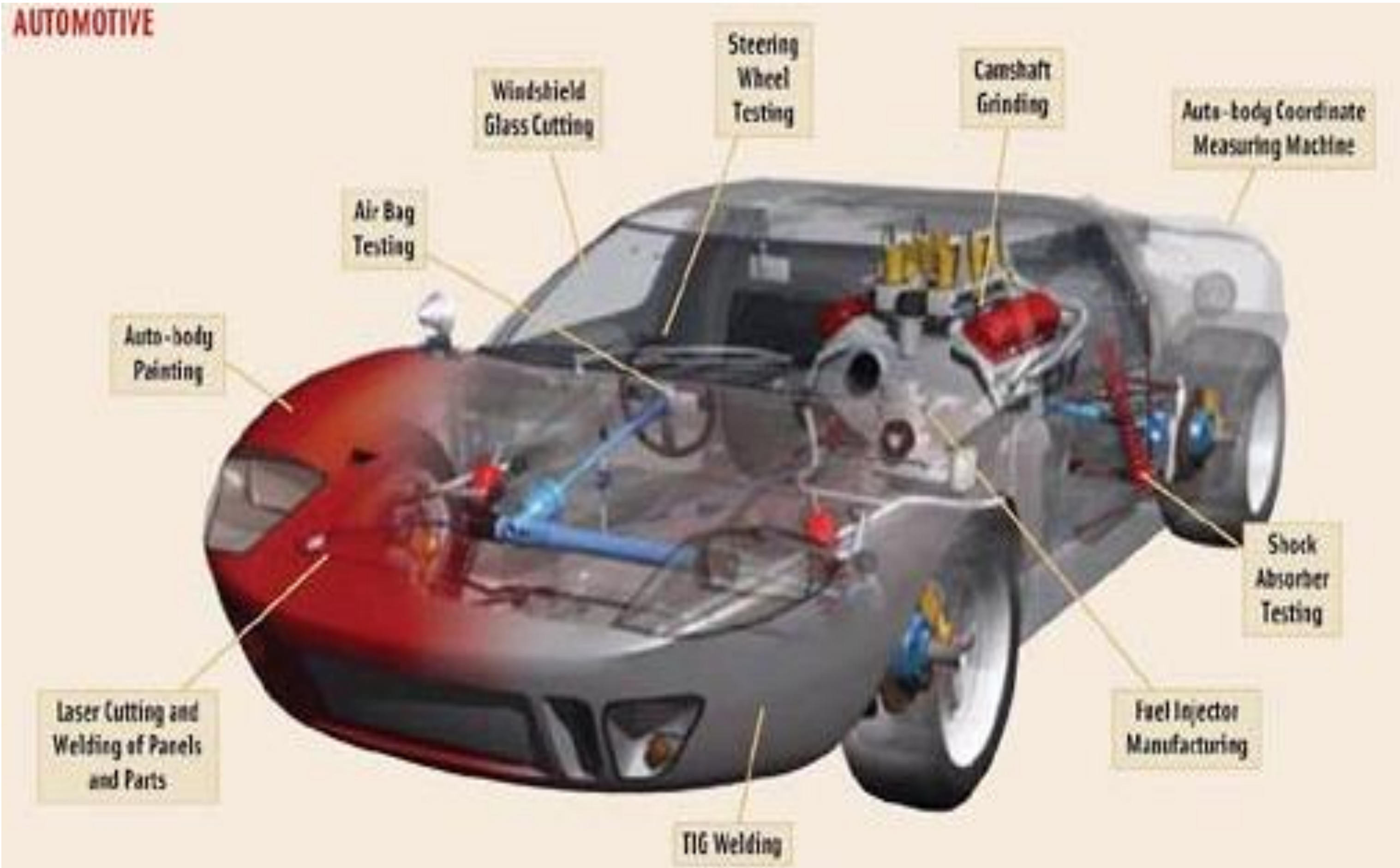
The Sky Train in Vancouver, Canada—An Automated Transit System

Is this a "Mechatronic" System?

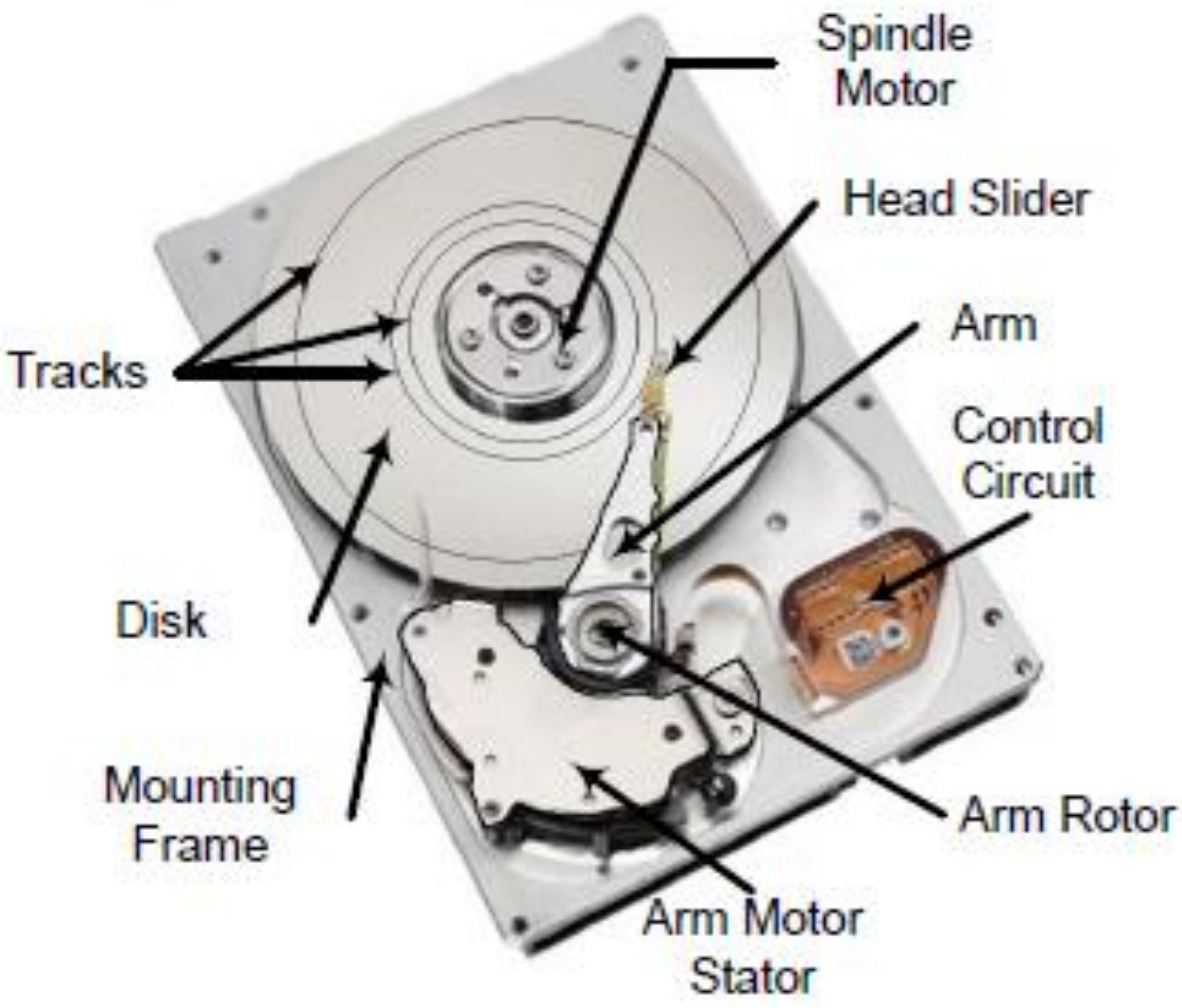
Humanoid robot:



Automobile: Is This a "Mechatronic" System?



Is This a "Mechatronic" System?



Mechatronic Approach: **Integrated, Unified, Unique (Optimal), Systematic**

Mechatronics

What is a Mechatronic System?

- An electromechanical system?
- A system with sensors, actuators, and controllers?
- A multi-physics system?
- A multi-domain system?
- A system designed by considering all domains/components simultaneously?
- A system designed by using similar (analogous) methods for the different domains?
- An optimized system?
- A system designed through a mechatronics approach? Then, what is the mechatronic approach?

Exploring the Definition of a Mechatronic System

- There is some validity of everything that was listed before
- The key aspects of the popular definition: Synergistic application; multi-domain (mechanics, electronics, control engineering, computer science); electromechanical products and systems; integrated design

The Established Definition of Mechatronics

Synergistic application of mechanics, electronics, control engineering, and computer science in the development of electromechanical products and systems, through integrated design

Our "Extended" Definition for a Mechatronic System

- A multi-physics system (not limited to electro-mechanical)
- Approach used in the development:
  - Integrated (concurrent, synergistic, etc.) approach → All domains are considered together
  - Unified (analogous, etc.) approach → similar approaches are used for the different domain
  - Unique result → typically, optimal result (only one best solution)
  - Systematic approach → Clearly articulated set of steps are used in the development

Note: These considerations are applicable to modeling, design, instrumentation, control, operation, etc.

Questions on Mechatronics

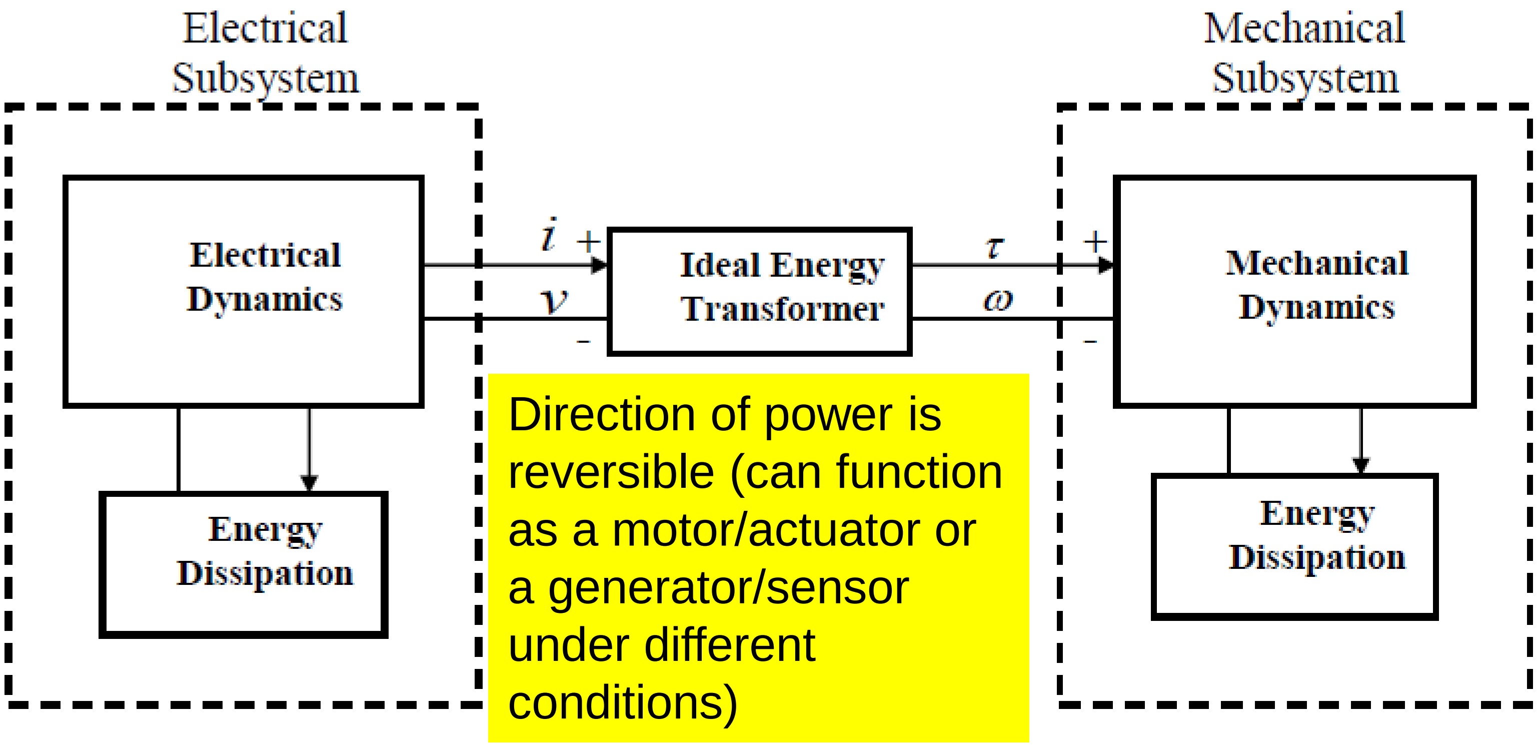
- **Meaning of Mechatronics?**
- **Key issues in the development of a mechatronic product?**
- **Advantages of Mechatronics?**

Discussion Topic on Mechatronics

The mechatronic approach is said to be: Integrated, Unified, Systematic, and Unique.

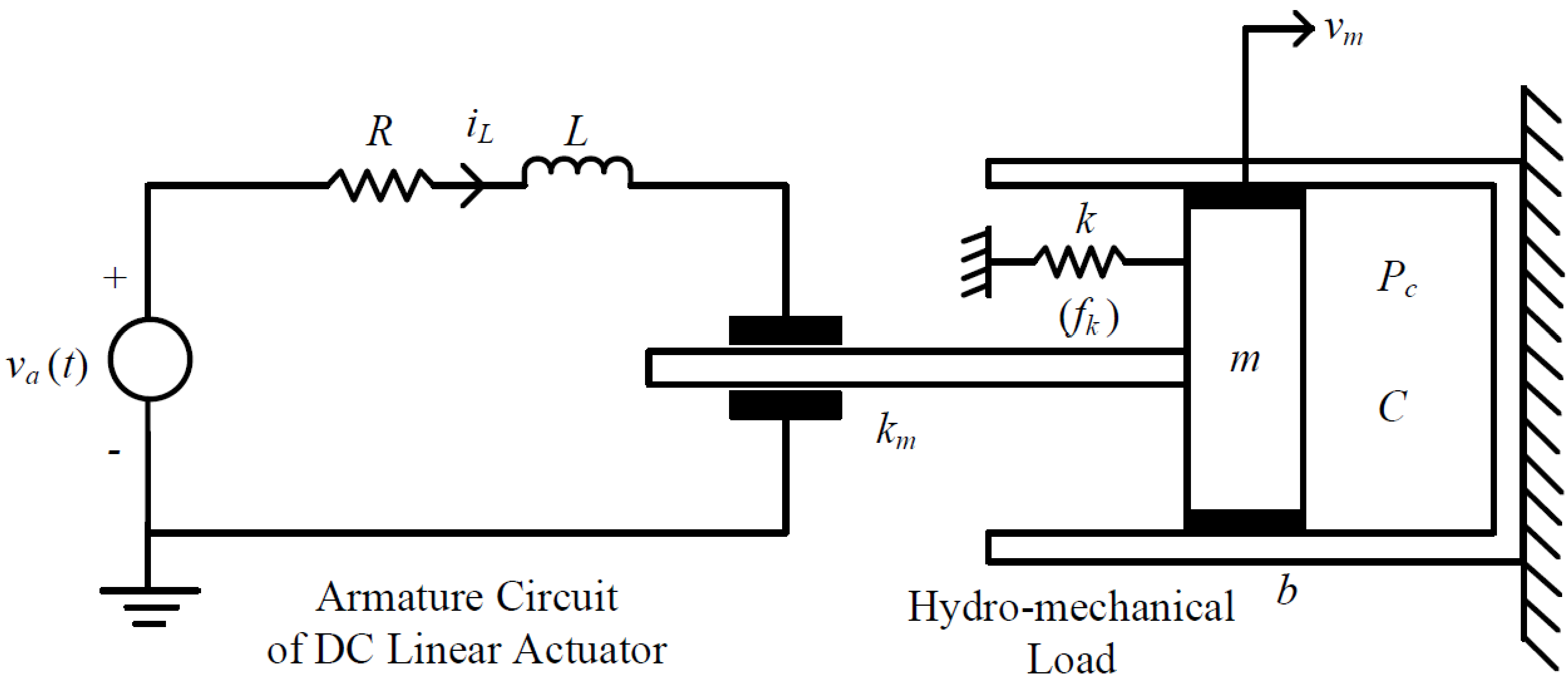
Why? What are its advantages?

Justification for an "Integrated" Approach



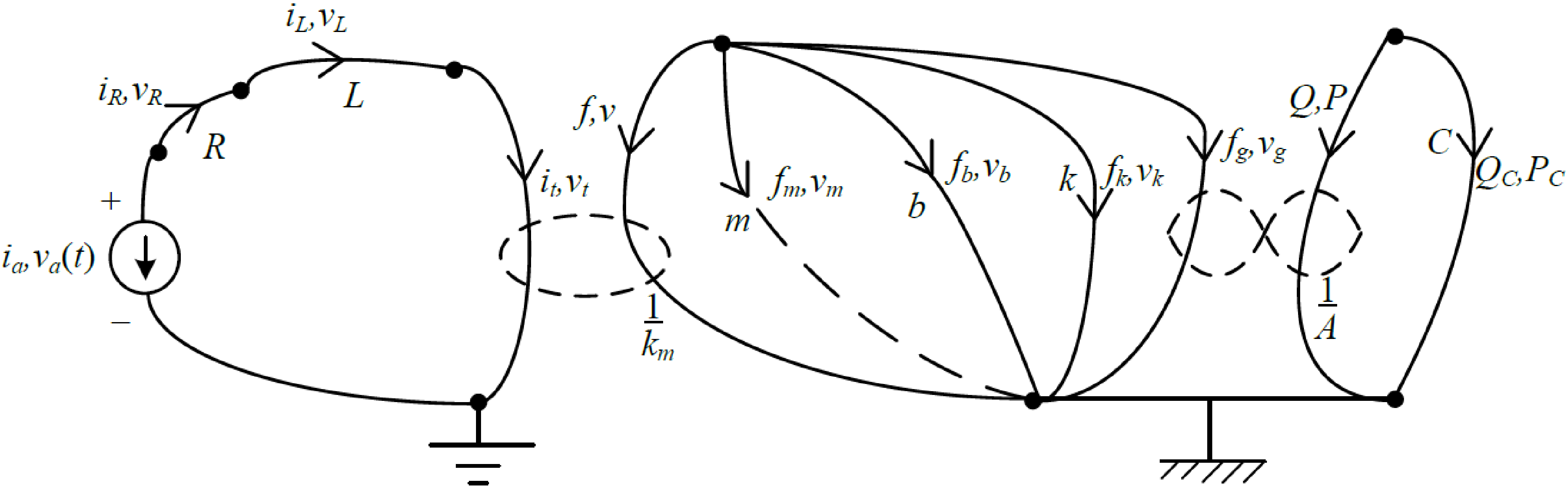
A model for mixed-domain (electro-mechanical) component interconnection

An Example to Justify the "Unified" Approach

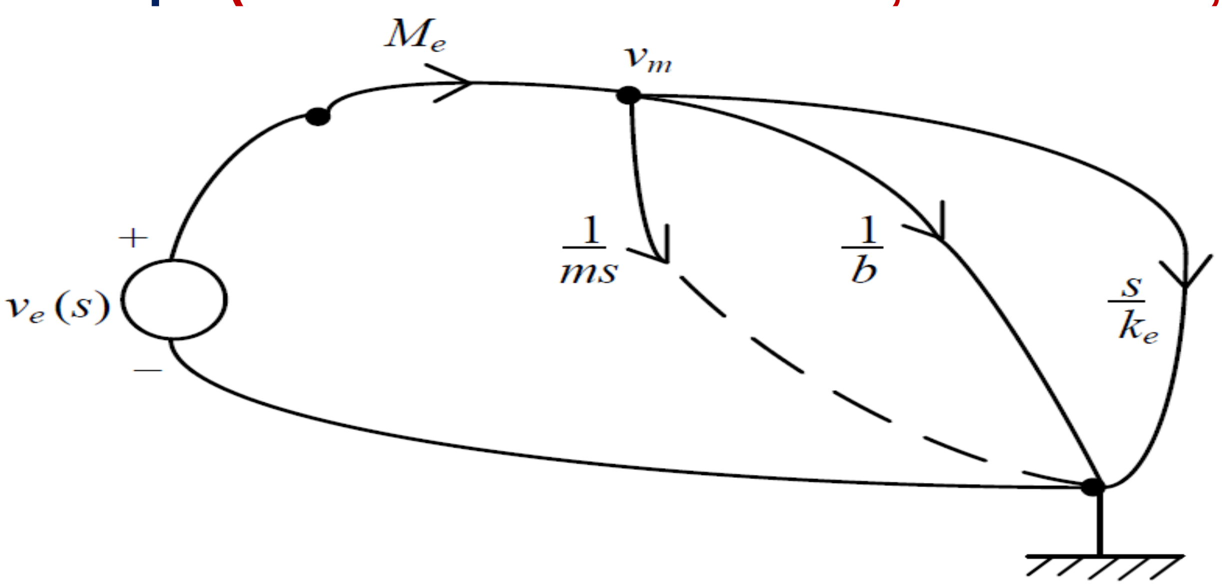


A DC linear motor-driven hydro-mechanical load

An Example to Justify the "Unified" Approach (Cont'd)



Linear Graph (Mixed-domain—electrical, mechanical, fluid)



Equivalent Linear Graph Entirely in the Mechanical Domain

Motivation for Mechatronic Products

- Sequentially designed and instrumented components of existing "multi-domain" systems are not optimally matched; **coupling/interactions are not considered**
- High potential for improvement through **concurrent, unified, and optimal design and instrumentation**

Benefits of Mechatronic Design and Instrumentation:

- Optimality and better component matching
- Increased efficiency
- Cost effectiveness
- Ease of system integration and expansion/enhancement
- Compatibility & ease of cooperation with other systems
- Improved controllability
- Increased reliability
- Increased product life

"Why" (for each benefit)?

“Mechatronic” Instrumentation

Mechatronic Approach to Instrumentation—Concurrent & Unified Instrumentation

- **Treat instrumentation as an integral part of design**
- **Design/incorporate the instrumentation concurrently**

(consider all aspects and components of instrumentation simultaneously)

- **Use similar techniques for different domains in the system**

Mechatronic Approach: **Integrated, Unified, Unique, Systematic**

Instrumentation Procedure

- Study the instrumented system (plant)
- Identify and group the system components (possibly, according to the physical domain—mechanical, electrical, fluid, thermal, etc.)
- Develop a preliminary System Architecture
- Formulate physical equations (Model)—for computer simulation, design, control, etc.
- Indicate operating requirements (performance specifications) for the plant

System level

Instrumentation Procedure (Cont'd)

- Identify constraints related to cost, size, weight, environment (e.g., operating temperature, humidity, dust-free or clean room conditions, lighting, wash-down needs)
- Select type and nature of sensors/transducers, actuators, signal conditioning devices (including interfacing and data acquisition hardware and software, filters, amplifiers, modulators, ADC, DAC, etc.)
- Establish the associated ratings/specifications of components (signal levels, bandwidths, accuracy, resolution, dynamic range, power, torque, speed, temperature, and pressure characteristics, etc.)
- Identify manufacturers/vendors for the components (model numbers, data sheets, etc.)

Component level

Instrumentation Procedure (Cont'd)

- **Revise system architecture (include controllers and/or control schemes if necessary). Revise the original computer model as necessary**
- **Carry out computer simulations. Make modifications to instrumentation until the system performance meets the specifications (A mechatronic optimization scheme may be used)**
- **Once acceptable results are achieved, acquire and integrate the actual components. Some new developments (designs) may be needed (new devices, interface hardware, fixtures, etc.)**

Commercially available components ➔ Instrumentation
New developments ➔ Design

Instrumentation and Design

Design:

Develop a system to meet the performance requirements

1. **Basic components of the system are identified during conceptual design**
2. **Their details, including parameter values, are decided during detailed design (final optimization is done here)**

- **Instrumentation is an integral part of design**
- **Both have the same end objective (meeting the specified performance)**

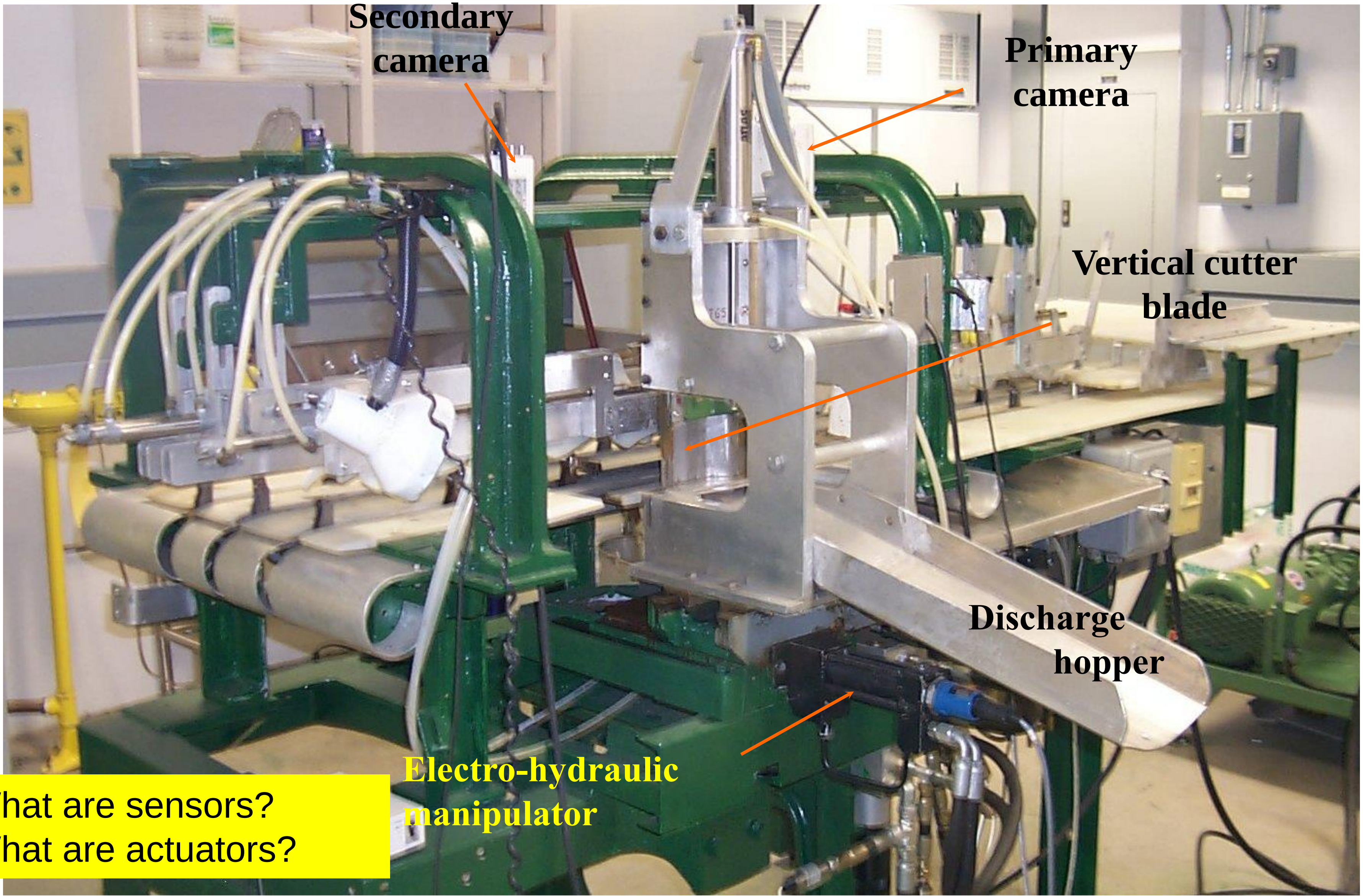
In Design: **Parameter choice can be infinite (in a continuous rage), particularly during optimization. Commercially unavailable components may have to be developed new.**

In Instrumentation: **Component choice is finite, and typically the components are commercially available**

Examples

Intelligent Iron Butcher

Is this an instrumentation problem or a design problem? **If not a mechatronic system, how would you make it one?**



What are sensors?
What are actuators?

Operation of the Intelligent Iron Butcher

Mobile Autonomous Sensor Module for Water Quality Monitoring

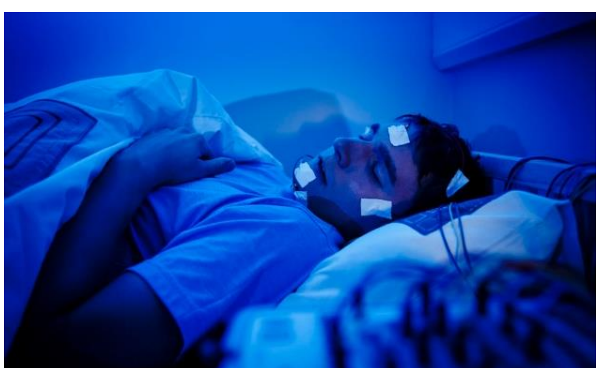
(a) Top view. (b) Back view. (c) Front-right view. (d) Side view.

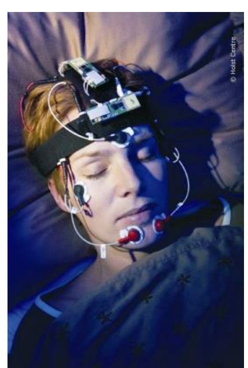
Is this an instrumentation problem or a design problem?

Industrial Automation Laboratory

SLEEP DISORDER MONITORING

Is this an instrumentation problem or a design problem?





Sleep Disorders

- Sleep Apnea (breathing interruption)
- Restless legs syndrome
- Insomnia

Symptoms

- Snoring
- Choking
- Cessation of abdominal & breathing

Risks

- Vulnerability to cardiovascular or metabolic diseases
- In worst cases, strokes or even death (in long term cases)

Thank you!

"Education is just the progressive Realisation of our ignorance"

Albert Einstein