Mechatronic Design Approach

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Mechatronics: Synergetic Integration of Different Disciplines

[Ref.] Prof. Rolf Isermann
Mechanical and Information Processing

[Ref.] Prof. Rolf Isermann
## Conventional vs. Mechatronic Design

<table>
<thead>
<tr>
<th>Conventional Design</th>
<th>Mechatronic Design</th>
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</thead>
<tbody>
<tr>
<td><strong>Added components</strong></td>
<td><strong>Integration of components (hardware)</strong></td>
</tr>
<tr>
<td>1 Bulky</td>
<td>Compact</td>
</tr>
<tr>
<td>2 Complex mechanisms</td>
<td>Simple mechanisms</td>
</tr>
<tr>
<td>3 Cable problems</td>
<td>Bus or wireless communication</td>
</tr>
<tr>
<td>4 Connected components</td>
<td>Autonomous units</td>
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<tr>
<td><strong>Simple control</strong></td>
<td><strong>Integration by information processing (software)</strong></td>
</tr>
<tr>
<td>5 Stiff construction</td>
<td>Elastic construction with damping by electronic feedback</td>
</tr>
<tr>
<td>6 Feedforward control, linear (analog) control</td>
<td>Programmable feedback (nonlinear) digital control</td>
</tr>
<tr>
<td>7 Precision through narrow tolerances</td>
<td>Precision through measurement and feedback control</td>
</tr>
<tr>
<td>8 Nonmeasurable quantities change arbitrarly</td>
<td>Control of nonmeasurable estimated quantities</td>
</tr>
<tr>
<td>9 Simple monitoring</td>
<td>Supervision with fault diagnosis</td>
</tr>
<tr>
<td>10 Fixed abilities</td>
<td>Learning abilities</td>
</tr>
</tbody>
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Multi-Level Control Architecture

- **Level 1**
  - low level control (feedforward, feedback for damping, stabilization, linearization)

- **Level 2**
  - high level control (advanced feedback control strategies)

- **Level 3**
  - supervision, including fault diagnosis

- **Level 4**
  - optimization, coordination (of processes)

- **Level 5**
  - general process management

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Design Steps

<table>
<thead>
<tr>
<th>Pure mechanical system</th>
<th>Precision Mechanics</th>
<th>Mechanical Elements</th>
<th>Machines</th>
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</thead>
<tbody>
<tr>
<td>1. Addition of sensors, actuators, microelectronics, control functions</td>
<td>![Diagram Icon]</td>
<td>![Diagram Icon]</td>
<td>![Diagram Icon]</td>
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<tr>
<td>2. Integration of components (hardware integration)</td>
<td>![Diagram Icon]</td>
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<tr>
<td>3. Integration by information processing (software integration)</td>
<td>![Diagram Icon]</td>
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<td>![Diagram Icon]</td>
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<td>4. Redesign of mechanical system</td>
<td>![Diagram Icon]</td>
<td>![Diagram Icon]</td>
<td>![Diagram Icon]</td>
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<tr>
<td>5. Creation of synergetic effects</td>
<td>![Diagram Icon]</td>
<td>![Diagram Icon]</td>
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</tbody>
</table>

Fully integrated mechatronic systems

Examples
- Sensors
- Actuators
- Disc-storages
- Cameras
- Suspensions
- Dampers
- Clutches
- Gears
- Brakes
- Electric drives
- Combustion engines
- Mach. tools
- Robots

The size of a circle indicates the present intensity of the respective mechatronic development step: 
- Large
- Medium
- Little

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Mathematical Models

- Mathematical process models for static and dynamic behavior are required for various steps in the design of mechatronic systems, such as simulation, control design, and reconstruction of variables.

- There are two ways to obtain these models:
  - *Theoretical modeling* based on first (physical) principles
  - *Experimental modeling (identification)* with measured input and output variables

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Simulation Methods

Simulation:
- digital/analog
- static behavior
- dynamic behavior

Simulation without time limitation:
- basic investigation of behavior
- verification of theoretical models
- process design
- control system design

Real-time simulation:
- process simulation:
  - hardware-in-the-loop simulation
  - training of operators
- controller simulation:
  - testing of control algorithms (controller prototyping)
  - process and controller simulation

Simulation faster than real time:
- model-based control systems
  - predictive control
  - adaptive control
- online optimization
- development of strategies, planning, scheduling
- components for real-time simulation

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Real-Time Simulation

- Real process simulated control system
- Simulated process simulated control system
- Simulated process real control system

(control design control prototyping) (control design "software-in-the-loop") (hardware-in-the-loop)

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Hardware-In-the-Loop (HIL)

- The *hardware-in-the-loop* simulation (HIL) is characterized by operating real components in connection with real-time simulated components. Usually, the control system hardware and software is the real system, as used for series production. The controlled process (consisting of actuators, physical processes, and sensors) can either comprise simulated components or real components,
PC-Based Hardware-in-the-Loop Simulation
Control Prototyping

- For the design and testing of complex control systems and their algorithms under real-time constraints, a real-time controller simulation (emulation) with hardware (e.g., off-the-shelf signal processor) other than the final series production hardware (e.g., special ASICS) may be performed. The process, the actuators, and sensors can then be real. This is called control prototyping.
Real-time simulation: hybrid structures. (a) Hardware-in-the-loop simulation. (b) Control prototyping.

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Integrated Design Issues

- Concurrent engineering of the mechatronics approach relies heavily on the use of system modeling and simulation throughout the design and prototyping stages.

- It is especially important that it be programmed in a visually intuitive environment.
  - block diagrams, flow charts, state transition diagrams, and bond graphs.
Integrated Design Issues

- Mechatronics is a design philosophy: an integrating approach to engineering design.

- Mechatronics makes the combination of actuators, sensors, control systems, and computers in the design process possible.

- Starting with basic design and progressing through the manufacturing phase, mechatronic design optimizes the parameters at each phase to produce a quality product in a short-cycle time.
Modeling vs. Experimental Validation

[Ref.] Craig and Stolfi
Hardware and Software Integration

[Ref.] Prof. Divdas Shetty
Concurrent Engineering

- Concurrent engineering is a design approach in which the design and manufacture of a product are merged in a special way.
  - It is necessary that the knowledge and necessary information be coordinated amongst different expert groups.

- The characteristics of concurrent engineering are
  - Better definition of the product without late changes.
  - Design for manufacturing and assembly undertaken in the early design stage.
  - Process on how the product development is well defined.
  - Better cost estimates.
  - Decrease in the barriers between design and manufacturing.
Concurrent Engineering

[Ref.] Bradley
Mechatronic Design Process

- Recognition of the need
- Conceptual design and functional specification
- First principle modular mathematical modeling
- Sensor and actuator selection
- Detailed modular mathematical modeling
- Control system design
- Design optimization

- Hardware-in-the-loop simulation
- Design optimization

- Deployment of embedded software
- Life cycle optimization

Information for future modules/upgrades

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Computer-Aided Systems: Important Features

- **Modeling:**
  - Block diagrams for working with understandable multi-disciplinary models that represent a physical phenomenon.

- **Simulation:**
  - Numerical methods for solving models containing differential, discrete, linear, and nonlinear equations.

- **Project Management:**
  - Database for maintaining project information and subsystem models for eventual reuse.

- **Design:**
  - Numerical methods for constrained optimization of performance functions based on model parameters and signals.
Computer-Aided Systems: Important Features

- **Analysis:**
  - Frequency-domain and time-domain tools

- **Real-Time Interface:**
  - A plug-in card is used to replace part of the model with actual hardware by interfacing to it with actuators and sensors.

- **Code Generator:**
  - Produces efficient high-level source code (such as C/C++) from the block diagram. The control code will be compiled and used on the embedded processor.

- **Embedded Processor Interface:**
  - Communication between the process and the computer-aided prototyping environment.
Mechatronic Key Elements

- Information Systems
  - Modeling and Simulation
  - Optimization
- Mechanical Systems
- Electrical Systems
  - DC and AC Analysis
  - Power
- Sensors and actuators
- Real-Time Interfacing
Information Systems

- Information systems include all aspects for information exchange
  - Signal processing, control systems, and analysis techniques

- The following are essential for mechatronics applications
  - Modeling and Simulation
  - Automatic control
  - Numerical methods for optimization.
**Information Systems: Modeling**

- **Modeling is the process of representing the behavior of a real system** by a collection of mathematical equations and logic.
- **Models can be static or dynamic**
  - Static models produce no motion, heat transfer, fluid flow, traveling waves, or any other changes.
  - Dynamic models have energy transfer which results in power flow. This causes motion, heat transfer, and other phenomena that change in time.
- **Models are cause-and-effect structures**—they accept external information and process it with their logic and equations to produce one or more outputs.
  - Parameter is a fixed-value unit of information
  - Signal is a changing-unit of information
- **Models can be text-based programming or block diagrams**
Simulation is the process of solving the model and is performed on a computer.

Simulation process can be divided into three sections:
- Initialization
- Iteration,
- Termination.
Optimization solves the problem of distributing limited resources throughout a system so that pre-specified aspects of its behavior are satisfied.

Resources are referred to as design variables, aspects of system behavior as objectives, and system governing relationships (equations and logic) as constraints.

Example:
- Objective: Maximize $V$ (volume) $V(L, W, H)$
- Constraints: System relationship: $V = LHW$
- $0 < L < 40$, $0 < W < 30$, $0 < H < 20$
Mechanical Systems

- Mechanical systems are concerned with the behavior of matter under the action of forces.
- Such systems are categorized as rigid, deformable, or fluid in nature.
  - Rigid-bodies assume all bodies and connections in the system to be perfectly rigid. (i.e. do not deform)
  - Fluid mechanics consists of compressible and incompressible fluids.
- Newtonian mechanics provides the basis for most mechanical systems and consists of three independent and absolute concepts:
  - Space, Time, and Mass.
  - Force, is also present but is not independent of the other three
Mechanics: Six Fundamental Laws

1. Newton’s First Law
2. Newton’s Second Law
3. Newton’s Third Law
5. Parallelogram Law for the Addition of Forces
6. Principle of Transmissibility
Electrical systems are concerned with the behavior of three fundamental quantities:
- Charge, current, and voltage

Electrical systems consist of two categories:
- Power systems and Communication systems

An electric circuit is a closed network of paths through which current flows.

Circuit analysis is the process of calculating all voltages and currents in a circuit given as is based on two fundamental laws:
- Kirchhoff’s current law: The sum of all currents entering a node is zero.
- Kirchhoff’s voltage law: The sum of all voltage drops around a closed loop is zero.
Electrical Systems

- For time-independent circuits (DC circuits), the following techniques are frequently used.
  - Parallel and series branch reductions
  - Node and loop analysis
  - Voltage and current divider reductions
  - Equivalent circuits (Thevenin and Norton equivalents)

- Additional techniques for time-dependent circuits, which include periodic (AC) as well as non-periodic or transient, are
  - Phasors
  - Natural and forced response
Electrical Systems: Power

- Energy is the capacity to do work various
  - Potential, kinetic, electrical, heat, chemical, nuclear, and radiant.
- Power is the rate of energy transfer, and in the SI unit system, the unit of energy is the joule and the unit of power is the watt (1 watt = 1 joule per second).

\[
\text{Instantaneous: } P(t) = v(t) \cdot i(t) \\
\text{Time averaged: } P_{AV} = \frac{1}{T} \int_{0}^{T} v(t) \cdot i(t) \cdot dt
\]
Sensors

- **Sensors are required to monitor the performance of machines and processes**

- Common variables in mechatronic systems are temperature, speed, position, force, torque, and acceleration.
  - Important characteristics: the dynamics of the sensor, stability, resolution, precision, robustness, size, and signal processing.

- **Intelligent sensors are available that not only sense information but process it well**
  - Progress in semiconductor manufacturing technology has made it possible to integrate sensor and the signal processing on one chip
  - Sensors are able to ascertain conditions instantaneously and accurately
  - These sensors facilitate operations normally performed by the control algorithm, which include automatic noise filtering, linearization sensitivity, and self-calibration.
Actuators

- *Actuation involves a* physical action on a machine or process. They can transform electrical inputs into mechanical outputs such as force, angle, and position.

- Actuators can be classified into three general groups.
  1. Electromagnetic actuators, (e.g., AC and DC electrical motors, stepper motors, electromagnets)
  2. Fluid power actuators, (e.g., hydraulics, pneumatics)
  3. Unconventional actuators (e.g., piezoelectric, magnetostrictive, memory metal)
Real-Time Interfacing

- Real-time interface provides data acquisition and control functions for the computer.

- Reconstruct a sensor waveform as a digital sequence and make it available to the computer software for processing.

- The control function produces an analog approximation as a series of small *steps*.

- *Real-time* interfacing includes:
  - A/D and D/A conversions
  - Analog signal conditioning circuits
  - Sampling theory.
MECHATRONIC APPLICATIONS
Automotive Industry

- Vehicle diagnostics and monitoring. Sensors to detect the environment; monitor engine coolant, temperature and quality; Engine oil pressure, level, and quality; tire pressure; brake pressure.

- Pressure, temperature sensing in various engine and power locations; exhaust gas analysis and control; Crankshaft positioning; Fuel pump pressure and fuel injection control; Transmission force and pressure control.

- Airbag safety deployment system. Micro-accelerometers and inertia sensors mounted on the chassis of the car measures car deceleration in x or y directions can assist in airbag deployment.

- Antilock brake system, cruise control. Position sensors to facilitate antilock braking system; Displacement and position sensors in suspension systems.

- Seat control for comfort and convenience. Displacement sensors and micro actuators for seat control; Sensors for air quality, temperature and humidity, Sensors for defogging of windshields.
Health Care Industry

- Medical diagnostic systems, non-invasive probes such as ultrasonic probe. Disposable blood pressure transducer;

- Pressure sensors in several diagnostic probes. Systems to control the intravenous fluids and drug flow;

- Endoscopic and orthopedic surgery. Angioplasty pressure sensor; Respirators; Lung capacity meters.

- Other products such as Kidney dialysis equipment; MRI equipment.
Robots
Aerospace Industry

- Landing gear systems; Cockpit instrumentation; Pressure sensors for oil, fuel, transmission; Air speed monitor; Altitude determination and control systems.

- Fuel efficiency and safety systems; Propulsion control with pressure sensors; Chemical leak detectors; Thermal monitoring and control systems.

- Inertial guidance systems; Accelerometers; Fiber-optic gyroscopes for guidance and monitoring.

- Automatic guided vehicles, space application; Use of automated navigation system for NASA projects; Use of automated systems in under water monitoring and control
Consumer Products
Consumer Industry

- Consumer products such as auto focus camera, video, and CD players; Consumer electronic products such as washing machines and dish washers.

- Video game entertainment systems; Virtual instrumentation in home entertainment.

- Home support systems; Garage door opener; Sensors with heating, ventilation, and air-conditioning system; Home security systems.
Production Machines
Industrial Systems and Products

- Monitoring and control of the manufacturing process; CNC machine tools; Advanced high speed machining and quality monitoring.

- Rapid prototyping; Manufacturing cost saving by rapid creation of models done by CAD/CAM integration and rapid prototyping equipment.

- Specialized manufacturing process such as the use of welding robots; Procedure for automatically programming and controlling a robot from CAD data.
3D Printing

Create physical plastic models from your 3D design in a matter of hours with our 3D printing service bureau: ThingLab.
Mechatronic System Example: DC Motor

[Ref.] Prof. Divdas Shetty
Conclusion

- Mechatronics design can lead to high quality and cost effective products
  - Traditional sequential manner do not possess optimum design capabilities.

- Concurrent design results in the development of intelligent and flexible mechatronic system

- Increasing demands on the productivity of machine tools and their growing technological complexity call for improved methods in future product development processes.