ITMO

Introduction to Electromechanical System Dynamics

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Outline

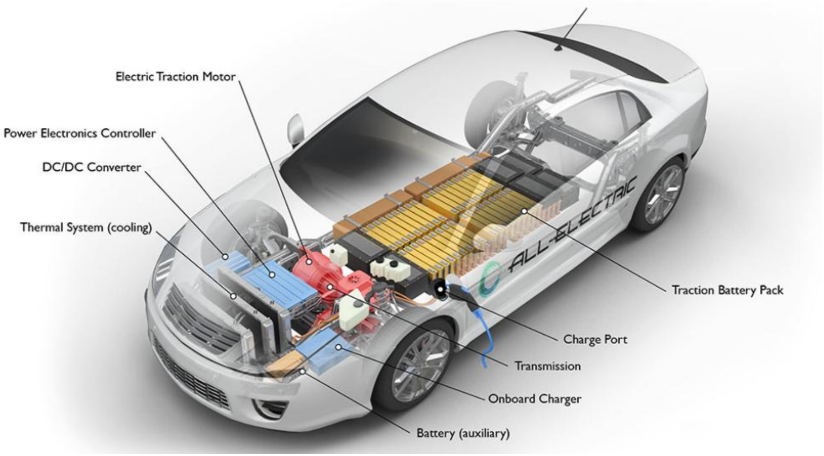
1. What Are Electromechanical Systems?
2. Applications Across Industries
3. What Will You Learn?
4. Why the dynamic is important for EMS
5. Fundamental Physical Laws
6. Why the Modeling is Important?
7. Numerical modelling

What Are Electromechanical Systems?

Definition: electromechanical systems are devices or systems that integrate electrical and mechanical components to perform a specific function.

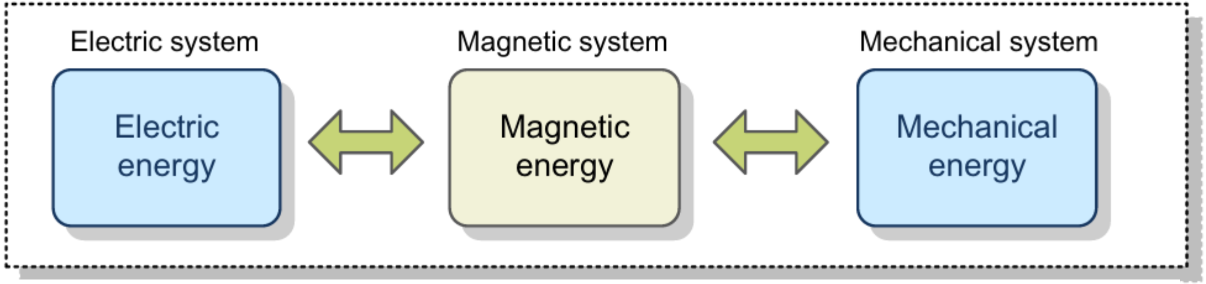
Examples:

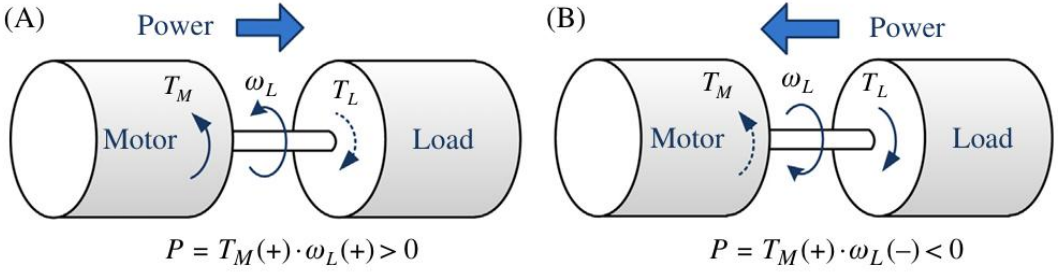
- Electric motors
- Robots
- Electric vehicles
- Sensors



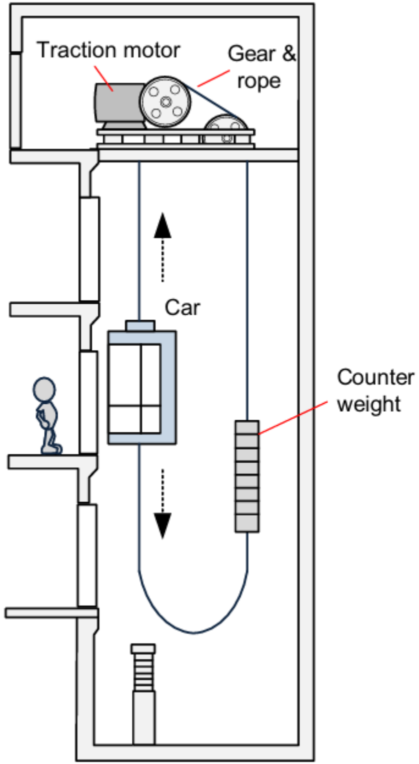
What Are Electromechanical Systems?

Electromechanical systems convert electrical energy into mechanical energy (e.g., motors) or vice versa (e.g., generators).





What Are Electromechanical Systems?



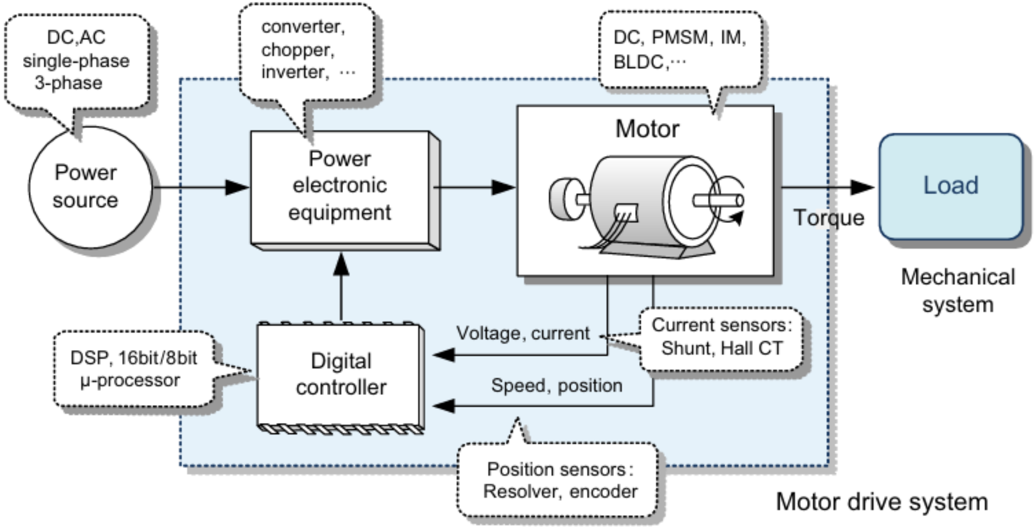
- When the car carrying people goes up and is heavier than the counterweight, the traction motor is needed to produce the forward direction torque, so it operates in the **motoring mode.**

- When the car carrying people goes down and is heavier than the counterweight, the traction motor is needed to produce the braking torque of the forward direction, so it operates in the **braking (generating) mode.**

What Are Electromechanical Systems?

Key Characteristics:

- Combine principles of electrical engineering, mechanical engineering, and control theory.



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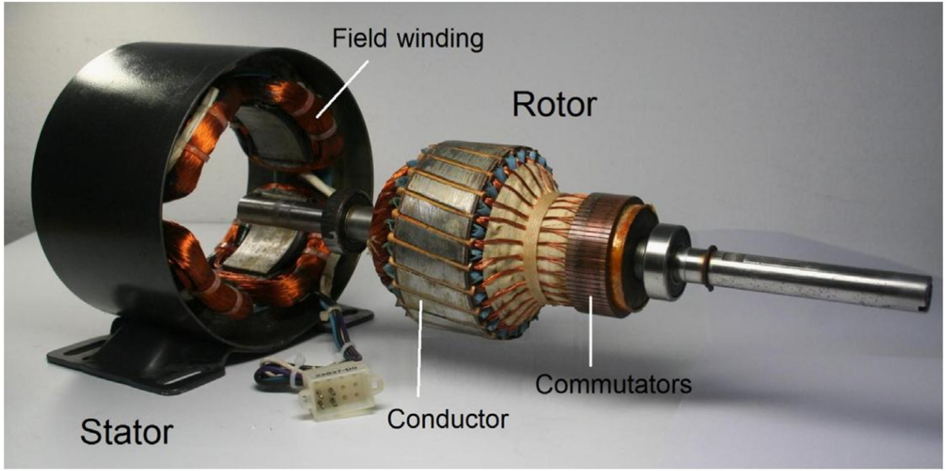
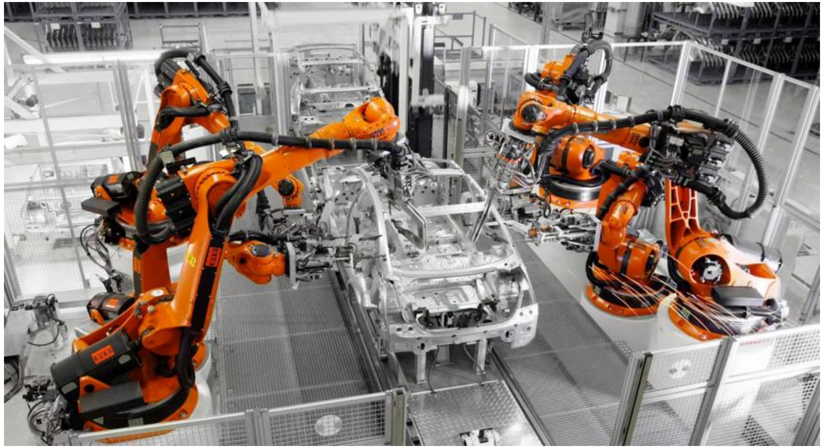


DC motor configuration

Applications Across Industries:

Industrial Automation:

- Robots and CNC machines for manufacturing.
- Conveyor systems and automated assembly lines.



Applications Across Industries:

Transportation:

- Electric vehicles (EVs), trains, and aircraft.
- Actuators and sensors in modern cars (e.g., anti-lock braking systems, power steering).

Applications Across Industries:

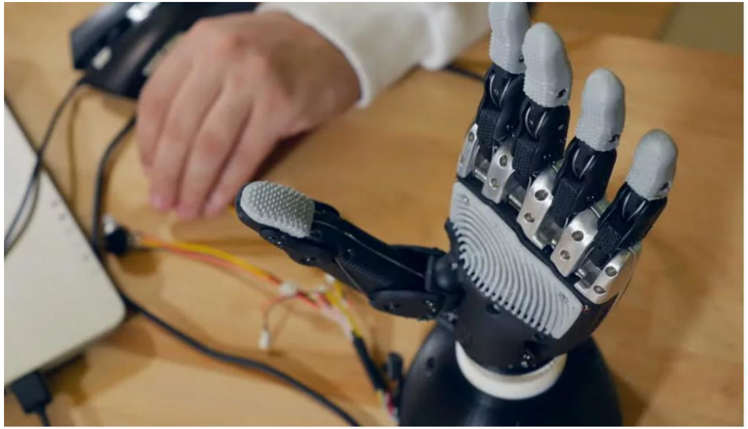
Energy Generation and Management:

- Generators in power plants.
- Wind turbines and solar tracking systems

Applications Across Industries:

Medical Devices:

- Robotic surgery systems.
- Prosthetics and rehabilitation devices



What Will You Learn?

1. How do **build and analyze** the dynamic models of electromechanical systems
2. Base principles of **electric** and **mechanical** parts dynamics
3. What **sensors** are usually used in electromechanical systems
4. Base principles of **control** of electromechanical systems

Why the dynamic is important for EMS

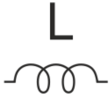
Definition of Dynamics in Electromechanical Systems:

- Dynamics refers to the study of **how** forces, torques, and energy interact within a system over **time**.
- In electromechanical systems, dynamics govern the interaction between electrical and mechanical components.

Base electrical components

Resistance

Inductance



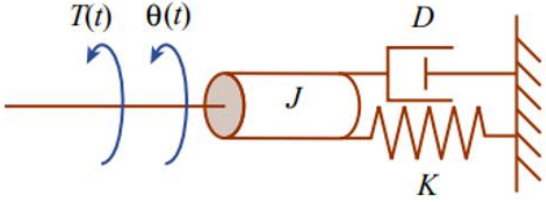
Capacity

Base mechanical components

Mass/inertia

Spring

Dampers



Why the dynamic is important for EMS

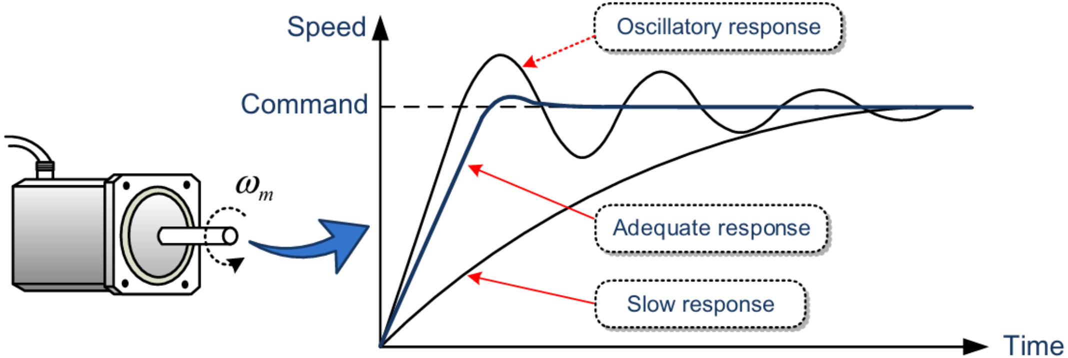
Importance of Dynamics:

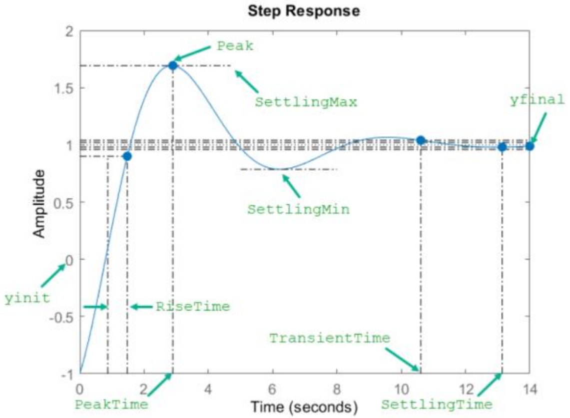
- Ensures smooth and efficient operation of systems like motors, generators, and actuators.
- Helps predict and control system behavior under varying conditions (e.g., load changes, external disturbances).
- Enables optimization of performance metrics such as settling time, overshooting, mean-squared error.

Why the dynamic is important for EMS

Examples of Dynamic Effects:

- Oscillations in motor startup or shutdown.
- Vibration and resonance in mechanical structures.
- Transient responses during sudden load changes.





Why the dynamic is important for EMS

System Stability and Control:

- Dynamics analysis helps ensure stability, preventing issues like overshooting, oscillations, or instability.
- Control algorithms (e.g., PID controllers) rely on dynamic models to regulate system behavior.

Energy Efficiency and Optimization:

- Understanding dynamics allows engineers to minimize energy losses during transitions and steady-state operations.
- *Example:* Optimizing the acceleration profile of an electric vehicle to reduce power consumption.

Why the dynamic is important for EMS

Real-World Applications:

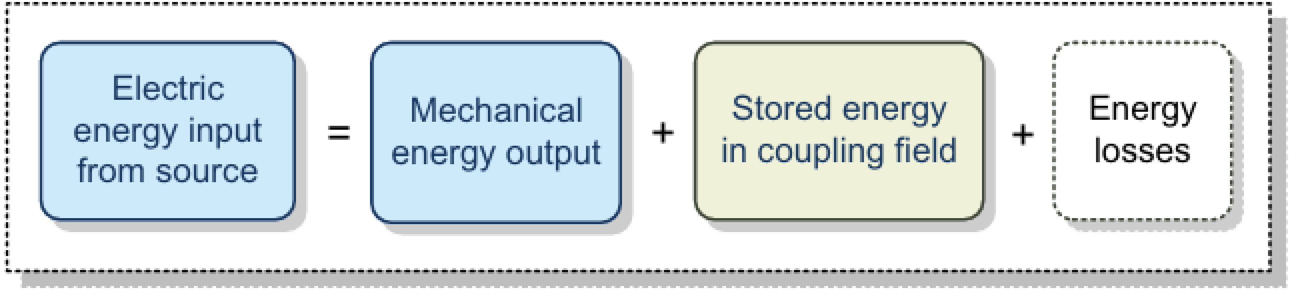
- Robotics: Precise motion control requires accurate dynamic modeling.
- Power Systems: Synchronization of generators depends on dynamic interactions.
- Aerospace: Actuators and control surfaces must respond dynamically to changing flight conditions

Challenges Without Proper Dynamics Analysis:

- Increased wear and tear due to uncontrolled vibrations or shocks.
- Reduced lifespan of components.
- Safety risks in critical applications (e.g., medical devices, industrial machinery).

Fundamental Physical Laws

The law of conservation of energy



Electromechanical energy conversion device

$$E_{in} = E_{out} + E_{losses} + E_{magnetic\ field}$$

Fundamental Physical Laws

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Kirchhoff`s laws

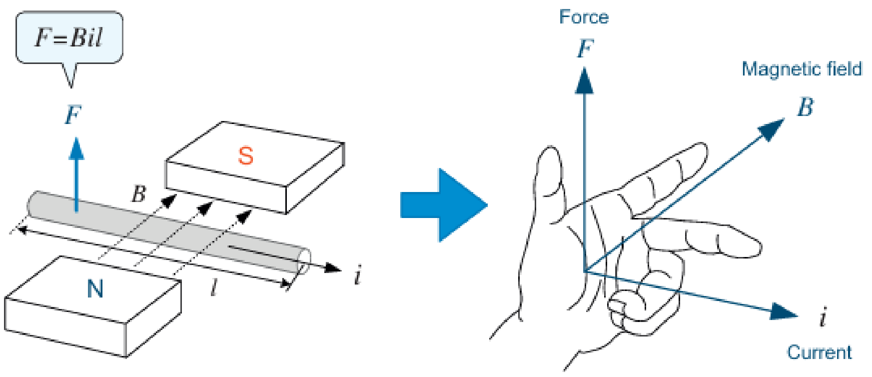
1st Kirchhoff`s law

$$\sum_k I_k = 0$$

2nd Kirchhoff`s law

$$\sum_i U_i = 0$$

Ampère’s Force



Fundamental Physical Laws

Newton`s 2nd law

For translational movement

$$\sum F = ma$$

m – *mass of the body*

a – *acceleration of the body*

For rotational movement

$$\sum T = J\varepsilon$$

J – *inertia of the body*

ε – *angular acceleration of the body*

Faraday's Law

$$V = -N\frac{d\Psi}{dt}$$

N – *number of turn in coil*

Ψ– *flux linkage*

Why the Modeling is Important?

Definition: Modeling is the process of creating a mathematical or computational representation of a system to simulate its behavior.

Purpose: It helps engineers understand how electromechanical systems interact with their environment.

Types of Models:

- Physical-based mathematical models (based on laws of physics).
- Data-driven models (using machine learning or experimental data).
- Hybrid models (combining physical and data-driven approaches).

Numerical Modeling

Why Use Numerical Modeling?

- Electromechanical systems are often too complex to analyze purely through analytical methods.
- Numerical modeling allows engineers to simulate system behavior under various conditions.
- It helps in designing, testing, and optimizing systems before physical prototyping.

Numerical Modeling

Key Software Tools:

MATLAB:

- A powerful platform for numerical computation and algorithm development.
- Ideal for solving differential equations and analyzing system dynamics.

Simulink:

- A graphical extension of MATLAB for modeling, simulating, and analyzing dynamic systems.
- Allows block diagram-based modeling of electromechanical systems.

ANSYS:

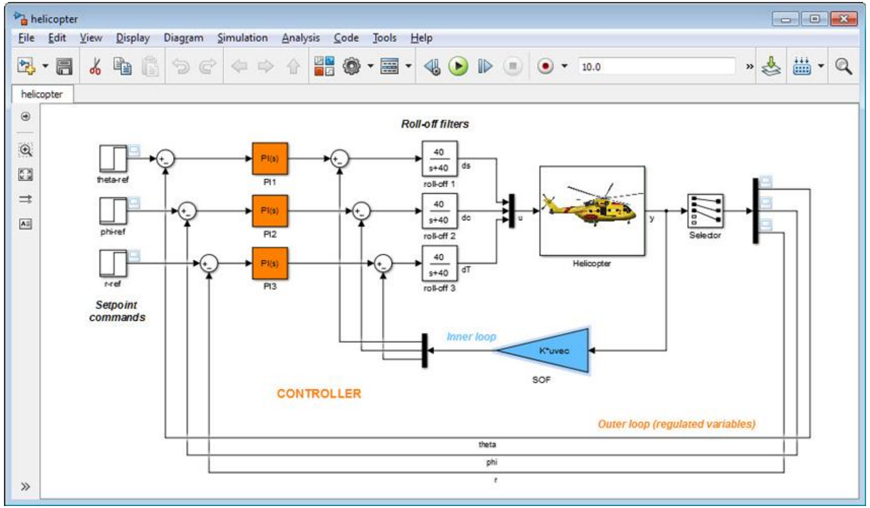
- Used for finite element analysis (FEA) and multiphysics simulations.
- Helps in studying electromagnetic fields, structural mechanics, and thermal effects.

COMSOL Multiphysics:

- Combines electrical, mechanical, and thermal simulations in a single environment.
- Useful for coupled electromechanical analyses.

Examples

This model is a mathematical representation, consisting of graphs, diagrams and other visualizations.



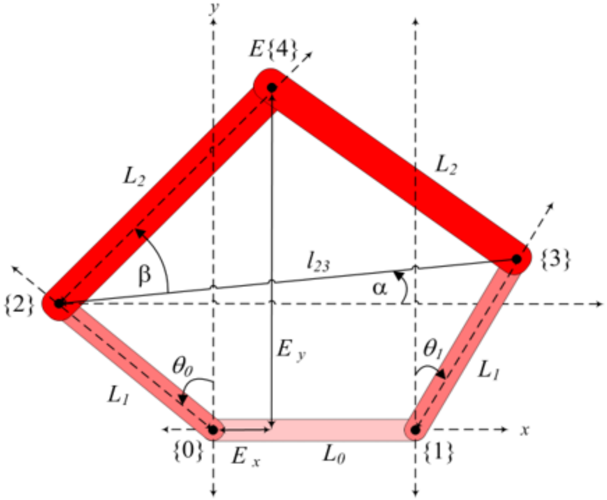
Helicopter VRT500

Source : https://ic.pics.livejournal.com/bmpd/38024980/5514067/5514067_original.jpg

Examples

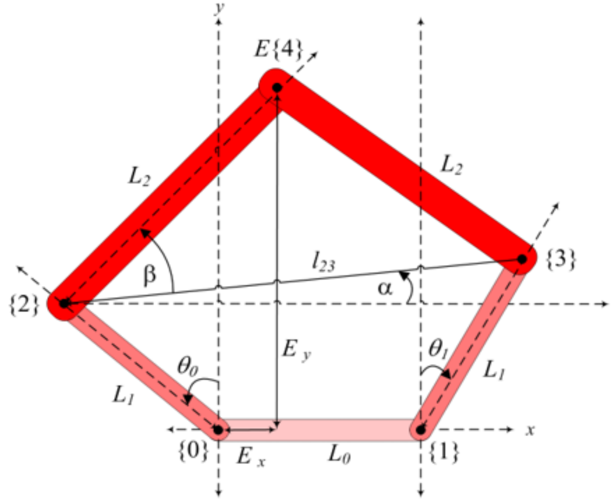
Examples

The original object



The model (kinematic diagram)

Examples



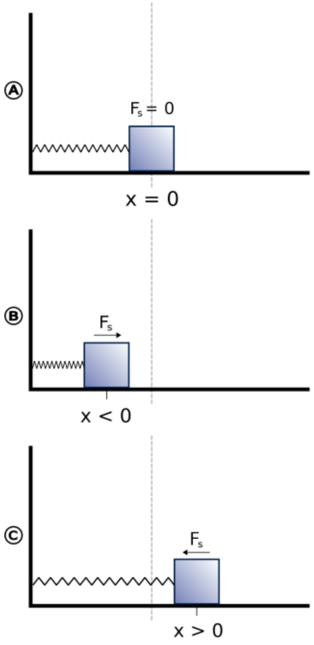
The model (kinematic diagram)

$$P_{2,x} = -L_1 \sin\theta_0$$
$$P_{2,y} = L_1 \cos\theta_0$$
$$P_{3,x} = L_1 \sin\theta_1 + L_0$$
$$P_{3,y} = L_1 \cos\theta_1$$
$$l_{23} = \sqrt{\left(P_{3,x} - P_{2,x}\right)^2 + \left(P_{3,y} - P_{2,y}\right)^2}$$

$$\alpha = \tan^{-1}\frac{P_{3,y} - P_{2,y}}{P_{3,x} - P_{2,x}}$$
$$\beta = \cos^{-1}\left(\frac{l_{23}}{2L_2}\right)$$
$$E_x = P_{2,x} + L_2 \cos(\alpha + \beta)$$
$$E_y = P_{2,y} + L_2 \sin(\alpha + \beta)$$
$$\theta_E = \alpha + \beta$$

The model (mathematical model)

Examples



Spring pendulum

Source : https://upload.wikimedia.org/wikipedia/commons/thumb/2/22/Harmonic_oscillator.svg/800px-Harmonic_oscillator.svg.png

Motion equation

$$\ddot{x} + \frac{c}{m}\dot{x} + \frac{k}{m}x = f(x)$$

Parameters:

m is the mass;

c is the coefficient of viscous friction;

k is the stiffness factor.

Examples

Examples

Motion equation

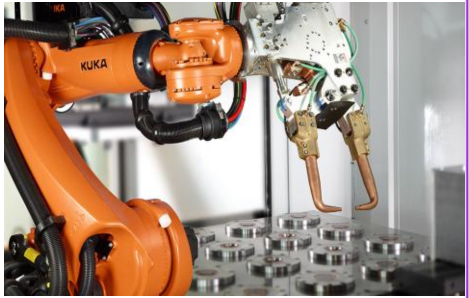
$$
\begin{cases}
L\dfrac{di_0}{dt} = u_0 - Ri_0 - c_e\Omega_1, \\
J_1\dfrac{d\Omega_1}{dt} = \dfrac{3}{2}c_e i_0 - k_s(\alpha_1 - \alpha_2) - k_d(\Omega_1 - \Omega_2) - M_{c1}, \\
J_2\dfrac{d\Omega_2}{dt} = k_s(\alpha_1 - \alpha_2) + k_d(\Omega_1 - \Omega_2) - M_{c2}, \\
\dfrac{d\alpha_1}{dt} = \Omega_1, \\
\dfrac{d\alpha_2}{dt} = \Omega_2.
\end{cases}
$$

Servo Drive

Source: https://uryupinsk.kypidetali.ru/images/products/2/7/3/1/7/0/372531.jpg

Telescope drive

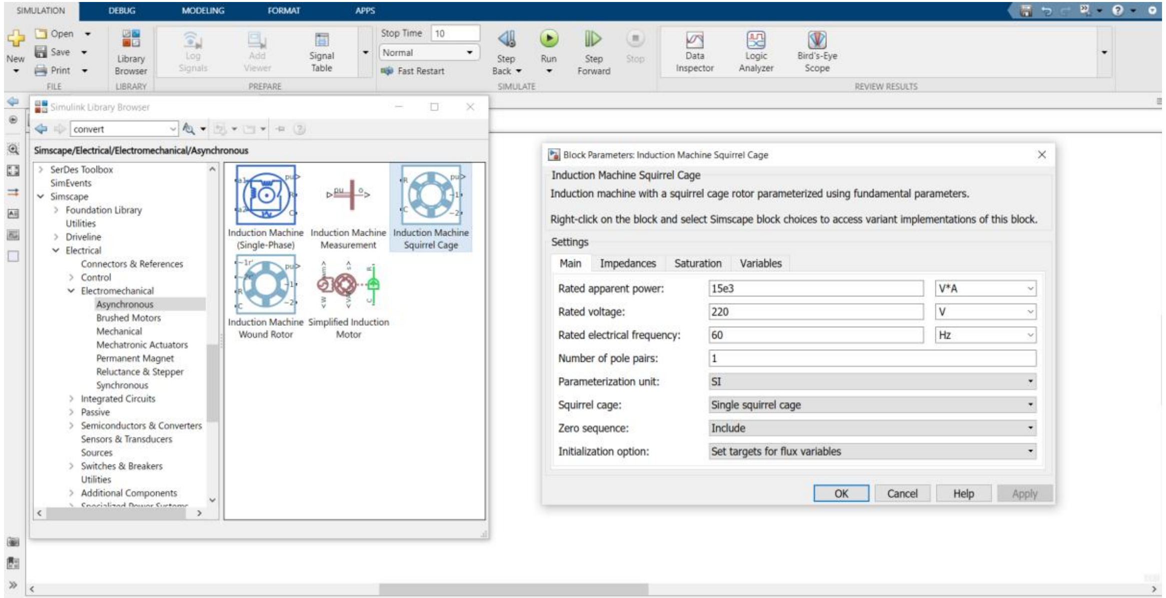
Source : https://bykvu.com/wp-content/uploads/images/2018/06/25/observatory3 . jpg



Manipulator link drive

Source : https://www.plm-ural.ru/sites/default/files/2020-04/kukaequalizingtech.jpg

Examples



Ready blocks of induction motors in Matlab / Simulink

Why the Modeling is Important?

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Design Optimization:

- Helps in identifying the best design parameters before physical prototyping.
- Reduces costs and time-to-market.

Performance Prediction:

- Allows engineers to predict system behavior under various conditions.
- Identifies potential failures or inefficiencies early in the design phase.

Why the Modeling is Important?

Safety and Reliability:

- Ensures systems operate within safe limits.
- Facilitates risk assessment and mitigation.

Scalability and Adaptability:

- Enables testing of systems at different scales (e.g., from small motors to large industrial machines).
- Supports adaptation to new technologies or requirements.

Examples

Physical prototyping

A physical model is created, which displays the main physical properties and characteristics of the object being modeled.

Preparation of the MS-21 model (scale 1:8) for testing in the TsAGI wind tunnel.

Source: https://twitter.com/UAC_Russia/status/560337107261345793/photo/1

Examples

The role of modeling in various stages of design

Servo Drive

Source: https://uryupinsk.kypidetali.ru/images/products/2/7/3/1/7/0/372531.jpg

Servo model at early stage

$$\begin{cases} L\dfrac{\mathrm{d}i_0}{\mathrm{d}t} = u_0 - Ri_0 - c_e\Omega, \\ J\dfrac{\mathrm{d}\Omega}{\mathrm{d}t} = \dfrac{3}{2}c_e i_0 - M_c, \\ \dfrac{\mathrm{d}\alpha}{\mathrm{d}t} = \Omega \end{cases}$$

for pre-calculations and energy performance evaluation

Examples

The role of modeling in various stages of design

Servo Drive

Source: https://uryupinsk.kypidetali.ru/images/products/2/7/3/1/7/0/372531.jpg

Servo model at the stage of control algorithms design

$$\begin{cases} L\dfrac{\mathrm{d}i_0}{\mathrm{d}t} = u_0 - Ri_0 - c_e\Omega_1, \\ J_1\dfrac{\mathrm{d}\Omega_1}{\mathrm{d}t} = \dfrac{3}{2}c_e i_0 - k_s(\alpha_1 - \alpha_2) - k_d(\Omega_1 - \Omega_2) - M_{c1}, \\ J_2\dfrac{\mathrm{d}\Omega_2}{\mathrm{d}t} = k_s(\alpha_1 - \alpha_2) + k_d(\Omega_1 - \Omega_2) - M_{c2}, \\ \dfrac{\mathrm{d}\alpha_1}{\mathrm{d}t} = \Omega_1, \\ \dfrac{\mathrm{d}\alpha_2}{\mathrm{d}t} = \Omega_2. \end{cases}$$

for control accuracy evaluation

Why the Modeling is Important?

Currently, mathematical modeling is an essential stage in the development of complex electromechanical systems.

There are numerous techniques and tools available for debugging algorithms based on mathematical models.

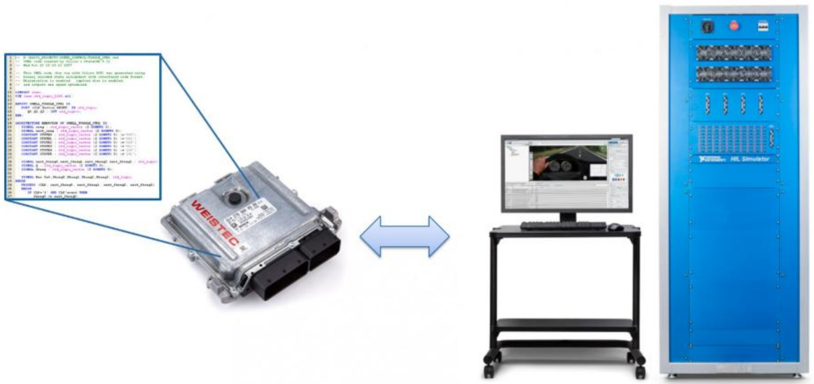
For instance, after developing algorithms in mathematical software, simulations using actual devices are employed:

- PiL (processor in loop) modelling
- HiL (hardware in loop) modelling

Automatic code generation is frequently utilized to convert algorithms created in MATLAB to microcontroller code.

That allows for a significant speedup in processing and seamless transitions from the modeling stage to the production of actual devices.

Examples



When testing individual electronic vehicle control units - a real vehicle is replaced by a simulation model

THANK YOU
FOR YOUR TIME!

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