MAE/ECE 5320 Mechatronics

2025 Spring semester

Lecture 09

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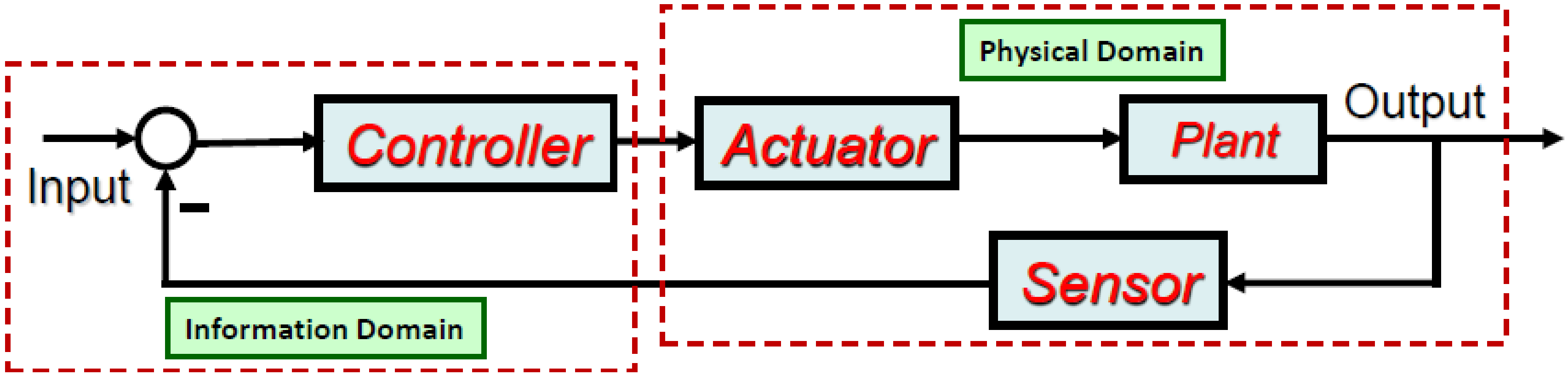
Content

- Mechatronic system and development
- Hardware selection

1) Motor selection
2) Sensor selection
3) MCU selection

- Summary of Mechatronics Lectures

Recall

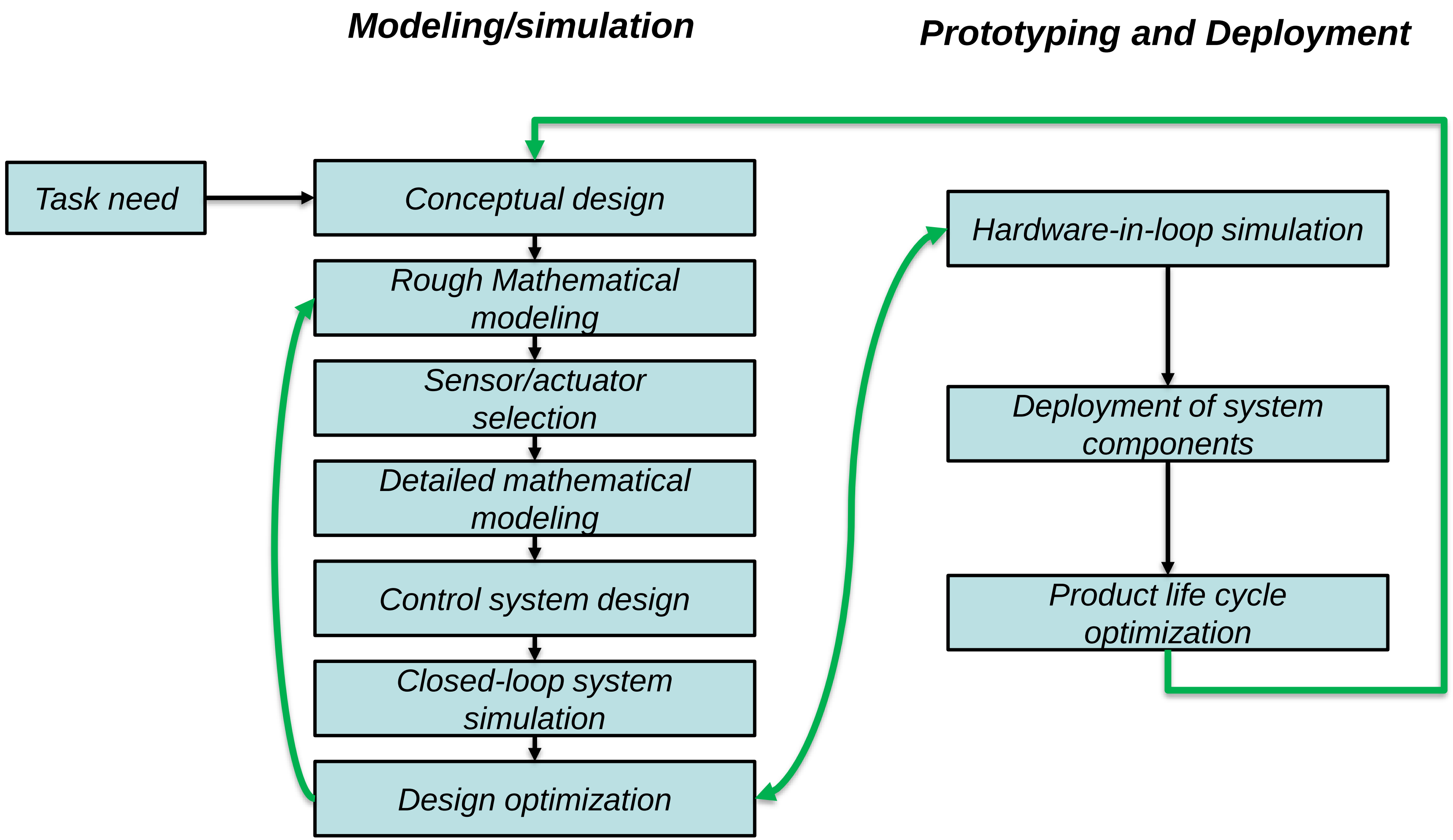


System components:

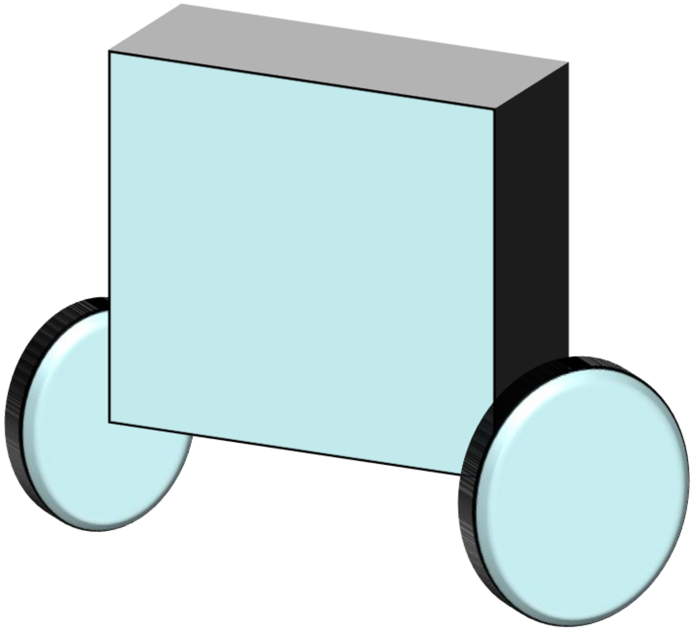
1. *Plant*
2. *Sensor*
3. *Actuator*
4. *Controller*

Basic architecture with ***information flow*** *and* ***power flow*** *has been introduced, in this lecture, the mechatronic* ***system development*** *and* ***selections of hardware****(system components) will be discussed.*

Mechatronic system development



Conceptual design & rough modeling



Two-wheel cart driven by two motors

+

Inverted pendulum (cube)

Recall last lecture:

Rough modeling of wheel(cart) and inverted pendulum

Wheel(Cart) modeling

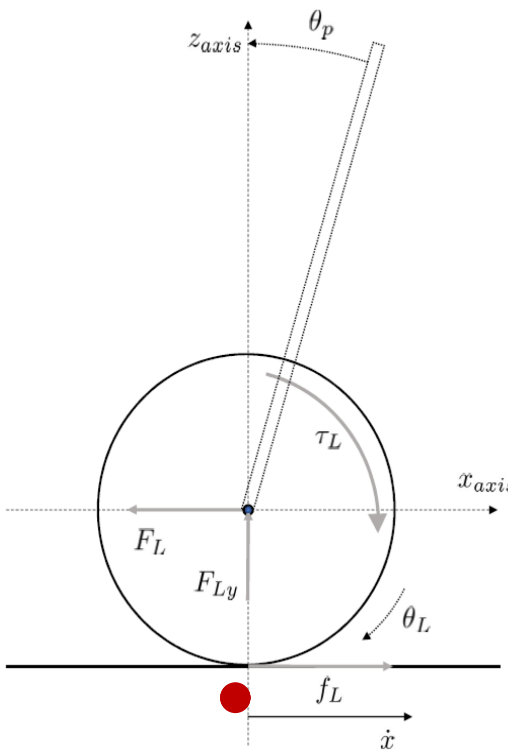
The motor torque τ_{mL} *works against motor friction torque* $\tau_f = K_f\dot{\theta}_L$ *and drive wheel(cart) by* τ_L*, thus*

$$\tau_L = \tau_{mL} - \tau_f \ (1)$$
$$\tau_R = \tau_{mR} - \tau_f \ (2)$$

Summation of the moments around the contacting point of ground and wheel (red spot in Figure)

$$\sum M_L = \tau_L - F_L r = \tau_{mL} - K_f\dot{\theta}_L - F_L r(3)$$

$$\sum M_R = \tau_R - F_R r = \tau_{mR} - K_f\dot{\theta}_R - F_R r(4)$$



From the Torque formula

$$\sum M_L = (I_\omega + r^2 m_\omega)\ddot{\theta}_L(5)$$

$$\sum M_R = (I_\omega + r^2 m_\omega)\ddot{\theta}_R(6)$$

Wheel(Cart) modeling

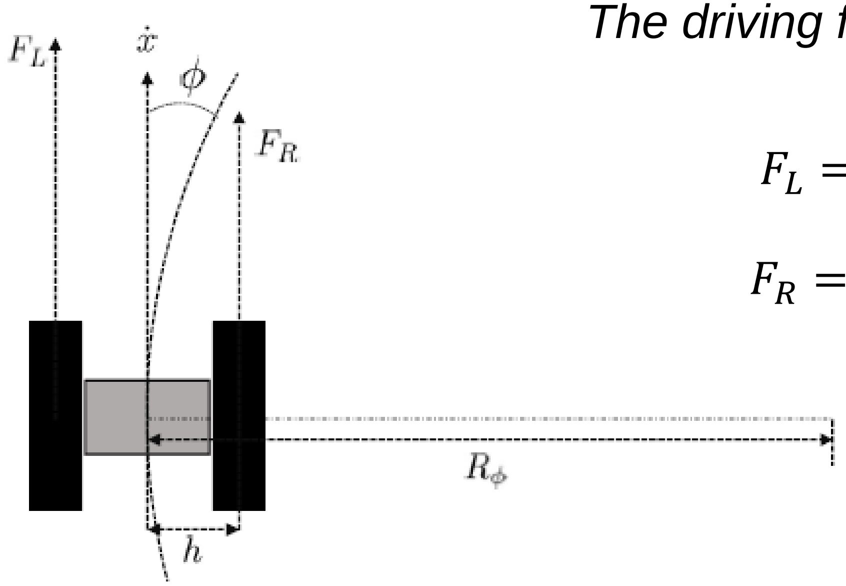
Assume there is no slip between wheel and ground, then the reaction forces from cart to left and right wheel are

$$F_L = \frac{\tau_{mL}}{r} - \frac{K_f \dot{\theta}_L}{r} - \frac{I_\omega \ddot{\theta}_L}{r} - m_\omega \ddot{\theta}_L r (7)$$

$$F_R = \frac{\tau_{mR}}{r} - \frac{K_f \dot{\theta}_R}{r} - \frac{I_\omega \ddot{\theta}_R}{r} - m_\omega \ddot{\theta}_R r (8)$$

Knowing $x_L = \theta_L r$, *so*

$$\dot{\theta}_L = \frac{\dot{x}_L}{r}, \ddot{\theta}_L = \frac{\ddot{x}_L}{r} (9)$$

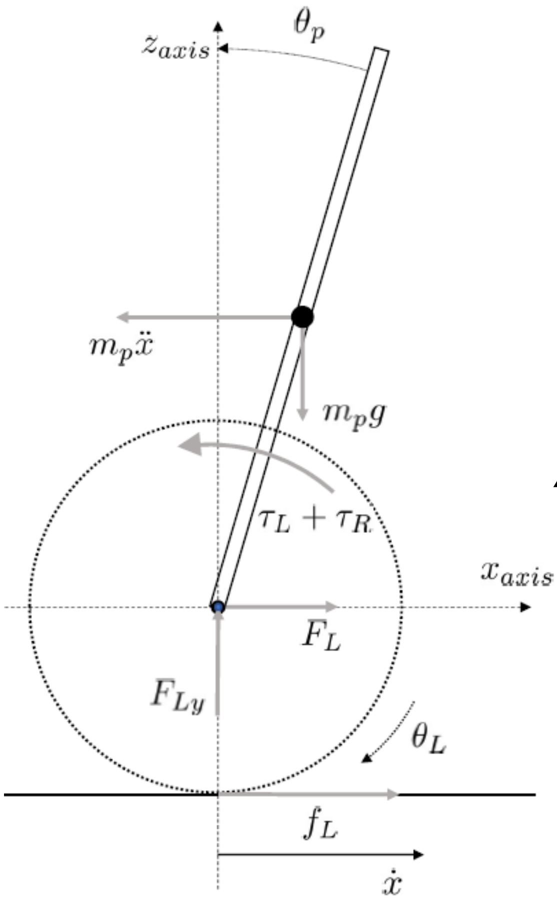


The driving forces can be expressed as

$$F_L = \frac{\tau_{mL}}{r} - \frac{K_f \dot{x}_L}{r^2} - \frac{I_\omega \ddot{x}_L}{r^2} - m_\omega \ddot{x}_L (10)$$

$$F_R = \frac{\tau_{mR}}{r} - \frac{K_f \dot{x}_R}{r^2} - \frac{I_\omega \ddot{x}_R}{r^2} - m_\omega \ddot{x}_R (11)$$

Pendulum modeling



Summation of forces on two wheels in x-axis

$$\sum F_x = F_L + F_R \quad (15)$$

The position of mass center of pendulum (black):

$$x_p = x + l sin\theta_p \quad (16)$$

Its speed can be differentiated as

$$\dot{x}_p = \dot{x} + l\dot{\theta}_p cos\theta_p \quad (17)$$

Acceleration is

$$\ddot{x}_p = \ddot{x} - l\dot{\theta}_p^2 sin\theta_p + l\ddot{\theta}_p cos\theta_p \quad (18)$$

By Newton's Law,

$$F_L + F_R = m_p\ddot{x}_p = m_p\left(\ddot{x} - l\dot{\theta}_p^2 sin\theta_p + l\ddot{\theta}_p cos\theta_p\right) \quad (19)$$

The angular motion of pendulum can be described by the Torque formula established at the joint of pendulum and wheel,

$$\left(I_p + m_p l^2\right)\ddot{\theta}_p = -m_p l\ddot{x} cos\theta_p + m_p lg sin\theta_p - (\tau_L + \tau_R) \quad (21)$$

Content

- ❑ Mechatronic system and development
- ❑ Hardware component selection

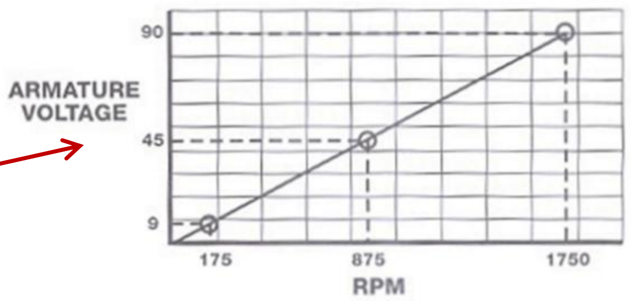
1) Motor selection
2) Sensor selection
3) MCU selection

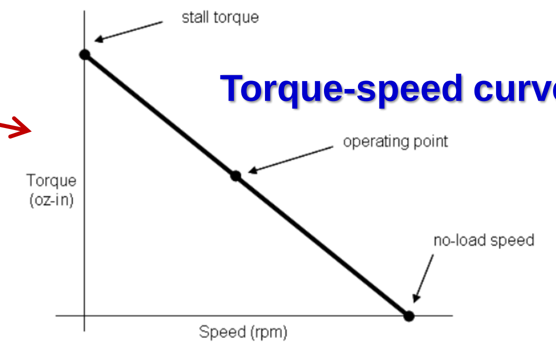
- ❑ Summary of Segway

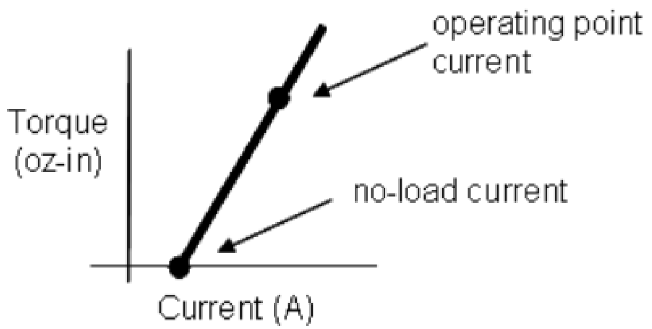
Recall characteristics of DC motor

Basic characteristics of DC motor

- ❑ With fixed load, motor shaft speed proportional to control voltage
- ❑ With fixed control voltage, shaft speed proportional to torque load
- ❑ Shaft torque proportional to motor current, independent of motor voltage
- ❑ Motor efficiency mainly impacted by its electric resistance and mechanical friction



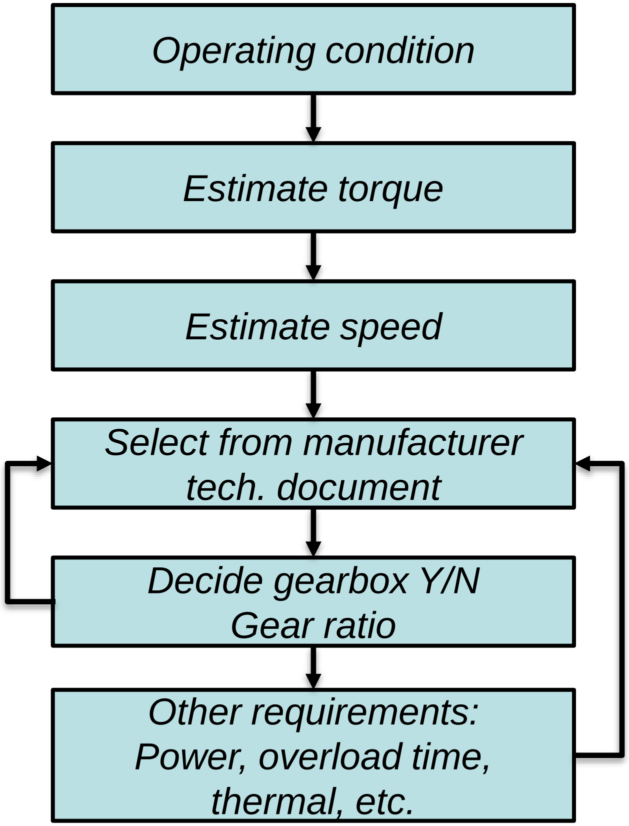




DC Motor selection

Requirements of main concerns:

1. *Speed*
2. *Torque*

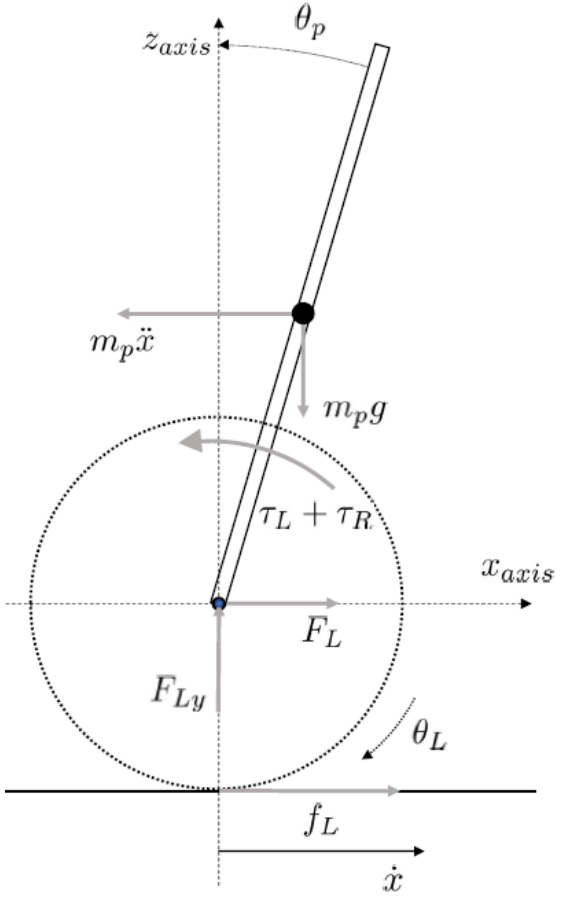


Notes:

1. *Gearbox is usually used to scale up/down motor rpm, some motors have installed gearbox.*
2. *Many motor manufacturers provide selection guideline for users.*
3. *Most motors can operate in overload condition for a short period, but with a lot heat generated.*

Sensor selection

Sensors are used for state estimation and provide feedback signal to controller. For example, In Segway, the <u>pitch angle</u> and motor <u>angle displacement</u> are to be estimated, thus <u>gyro & accelerometer</u> and <u>encoder</u> are needed.



Recall previous lecture of sensors for detailed sensor fusion.

Gyro, accelerometer and IMU

Selection criteria:

1. *Range;*
2. *Resolution;*
3. *Number of axes measured;*
4. *Bias rejection*
5. *Cost*

A. ***Select the suitable one, not the most accurate one***

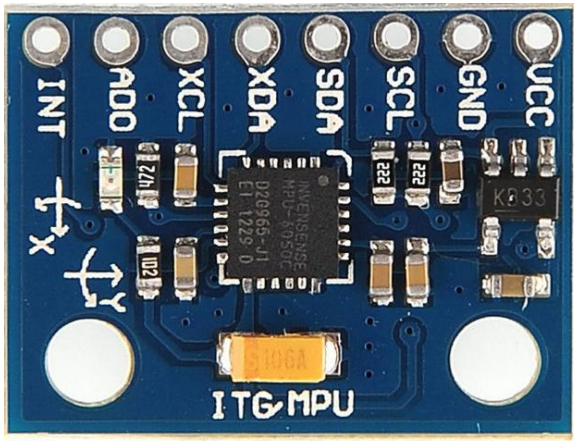
B. ***Fusion of low-cost sensors sometimes gives good performance as expensive ones***

IMU(Inertia Measurement Unit) provides platform synthesizing different sensors to provide estimation of orientation, position and velocity.

Some IMUs have mounted gyro and accelerometer, and is able to interface with microcontroller, which is convenient for users to select.

Recall: Accelerometer and rate gyro

MPU 6050: Gyro & Accelerometer



- **MPU-6050** is a single chip integrating a three-axis rate gyroscope sensor and a three-axis accelerometer sensor.
- Three 16-bit ADCs and three 16-bit ADCs are used for digitizing the gyroscope and accelerometer outputs, respectively

MEMS MEMS (Micro-ElectroMechanical Systems) advanced sensor technology is used to integrate micro-scale sensors into a single chip.

Encoder selection

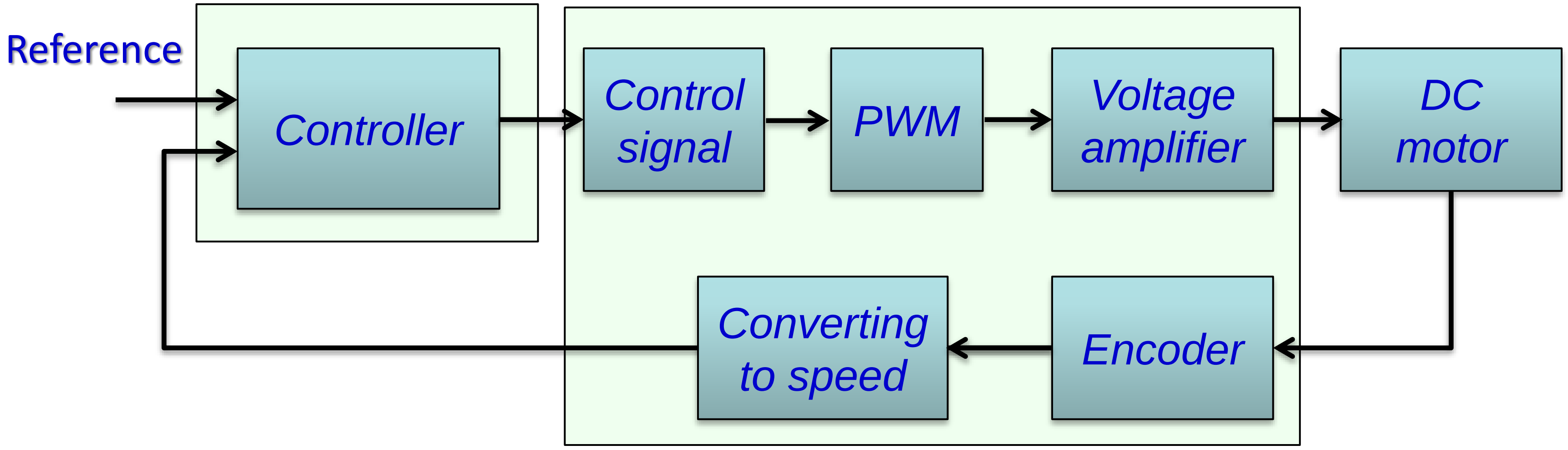
Resolution *is the most important selection criteria, but need to consider sampling frequency and processing capacity of microcontroller.*

A few recommended rules:

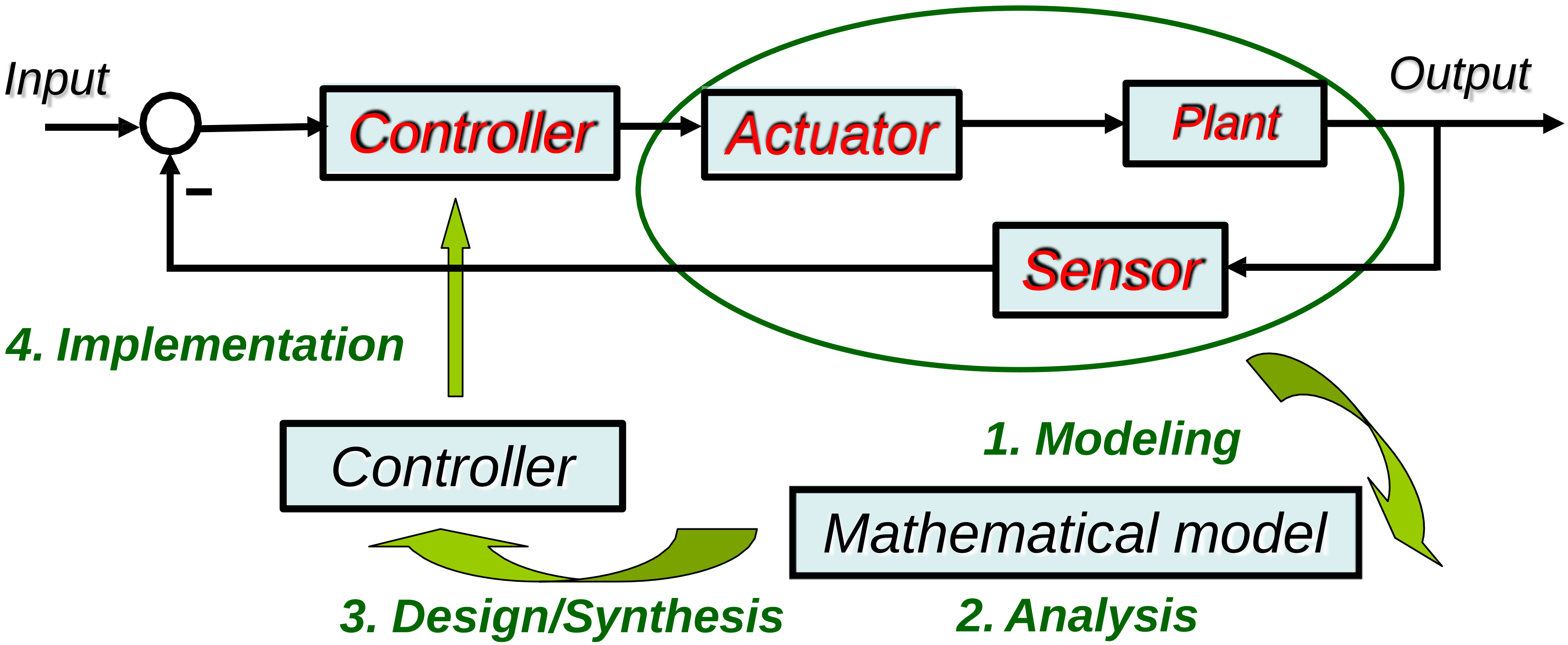
1. *Select a bit higher accurate encoder than required accuracy.*
2. *Select optical encoder for precision-positioning;*
3. *High-speed (>500 rpm) control: select encoder with low-number of states so that impulses can be processed fast;*
4. *Low-speed (<100 rpm)control: select encoder with high-number of states and fast controller*

Microcontroller selection

1. *Bit size*
2. *Processing capability*
3. *Interfaces or communications (serial, wifi)*
4. *Operating voltage*
5. *Number I/O pins*
6. *Memory requirements*
7. *Cost*



Summary- Modeling



develop mathematical models for

- *Electrical systems*
- *Mechanical systems*
- *Electro-mechanical system*

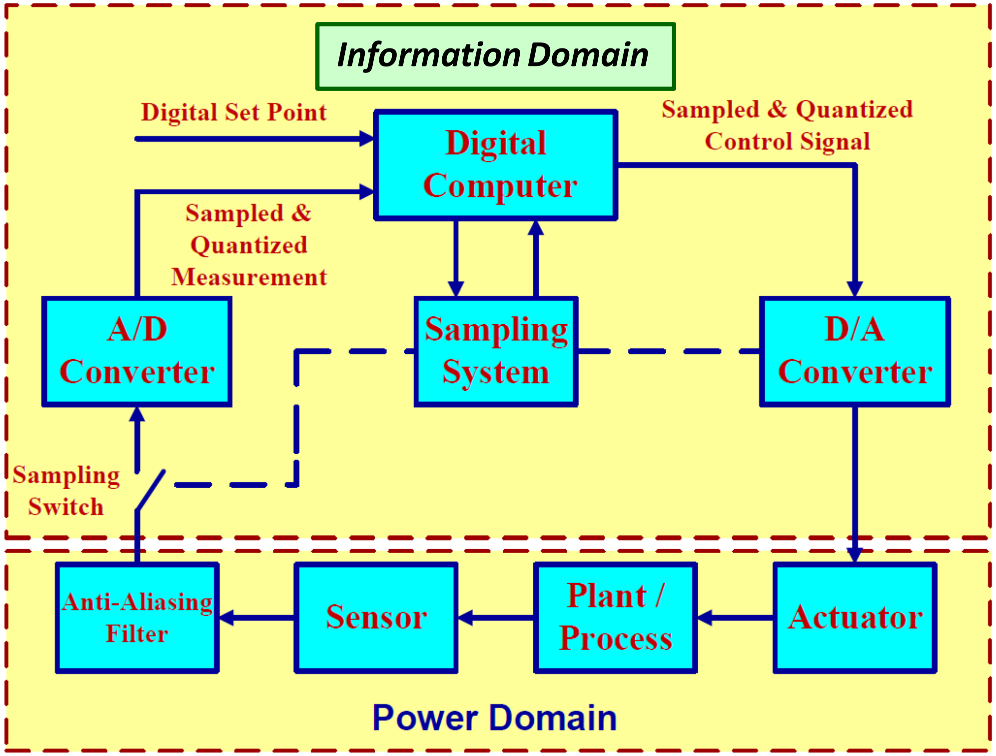
Electrical Systems:

- *Kirchhoff's voltage & current laws*

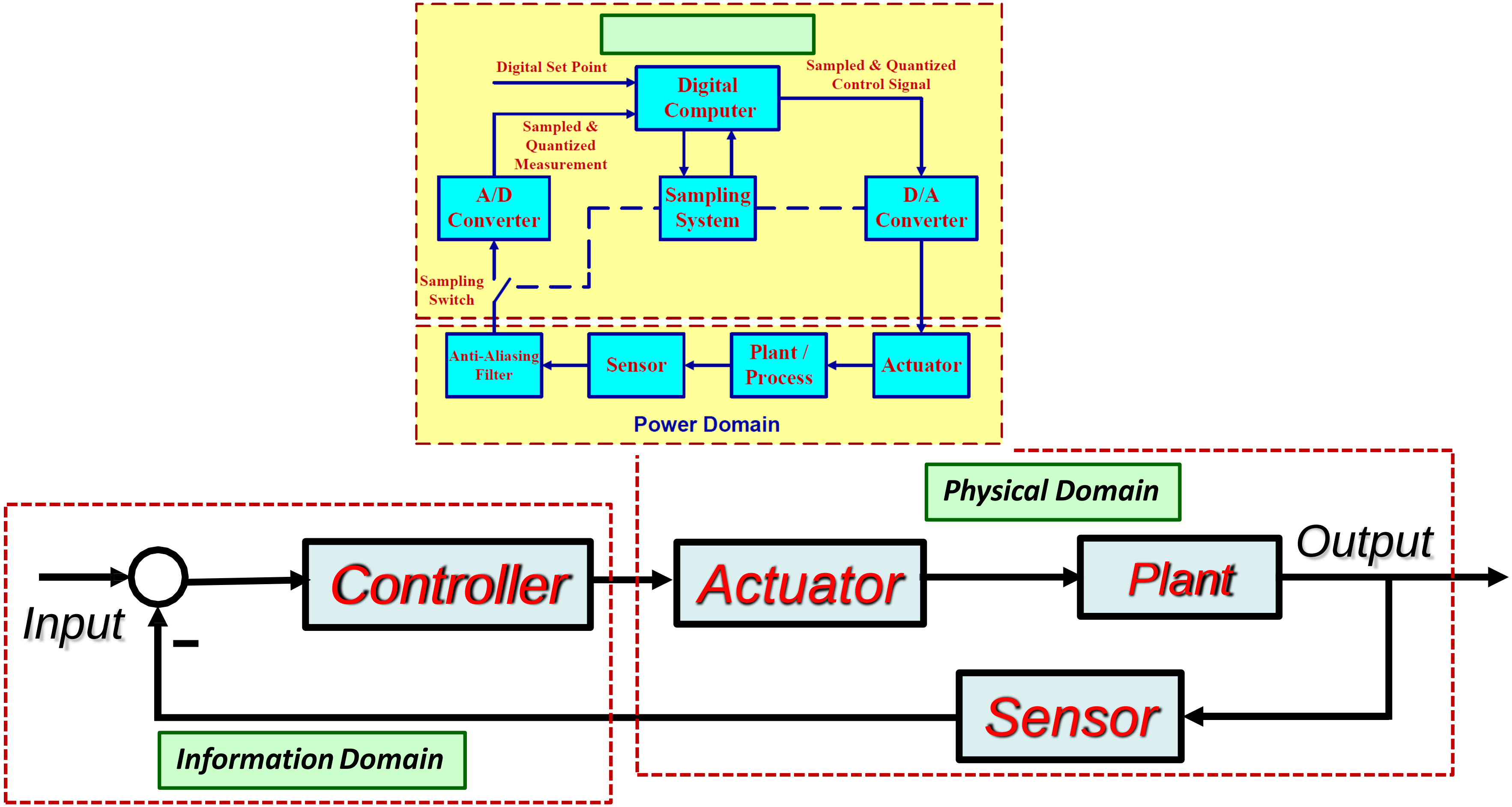
Mechanical systems:

- *Newton's laws*

Summary- Digital control



Summary



- ***Controller:*** *MCU-Arduino Uno, Simulink support package*
- ***Actuator:*** *DC motor, stepper motor, servo motor*

<u>Principles, characteristics and control methods,</u>

- ***Sensors:*** *IMU-MPU6050, Gyro & Accelerometer, encoder*

<u>Principles, readings to Simulink, Digital/analog reading, I2C communication</u>

- *Simulink support Arduino:*

<u>normal mode, external mode (monitor&tune), embedded mode to generate code(deploy&build)</u>

Kick-off of final project

See separate final project file