# Electrical Systems I

# Development of Integrated Vehicle Control System of "Fine-X" Which Realized Freer Movement.

Mitsuhisa Shida, Akira Matsui, Masayoshi Hoshino
Integrated System Engineering Div.
Toyota Motor Corporation.

# TOYOTA Freer Movement Control System

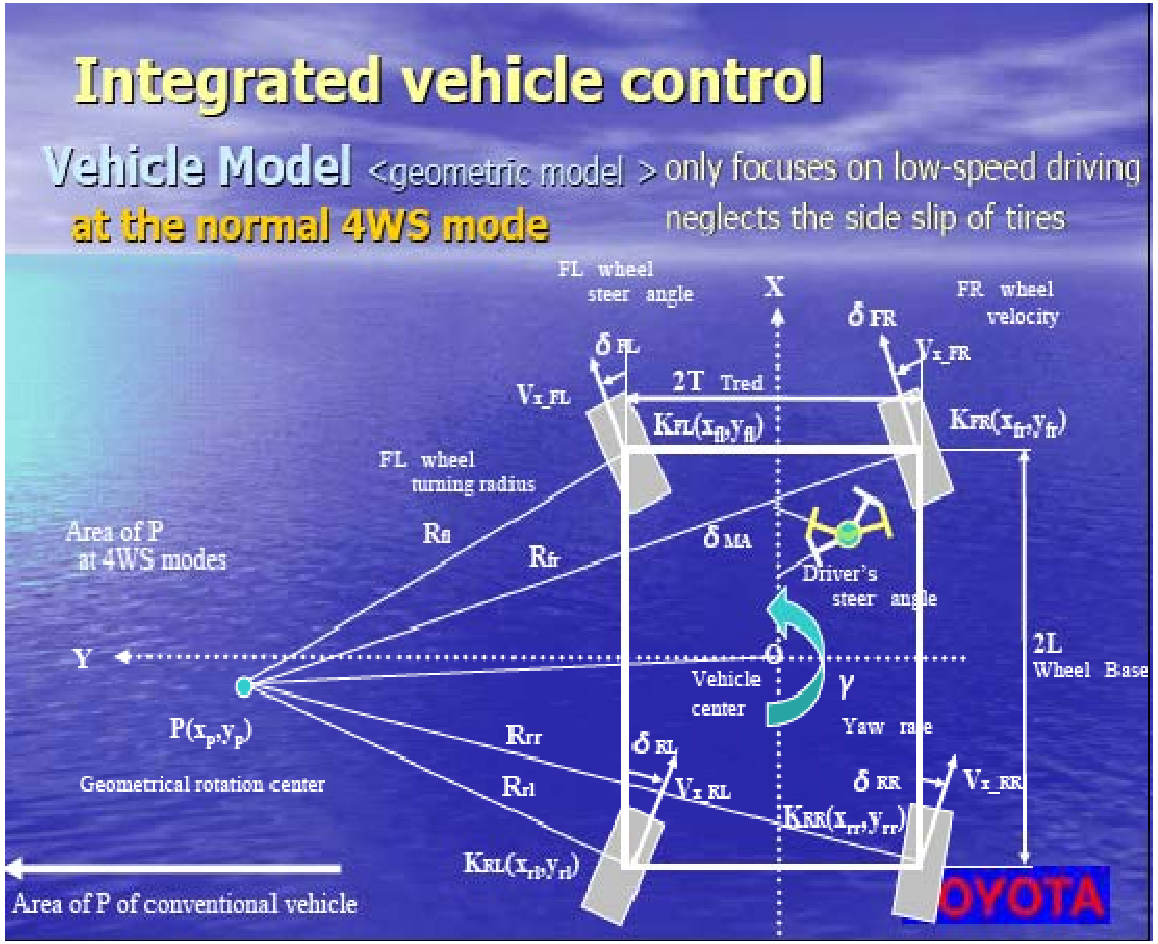

4Wheel independent drive

4wheel independent steering

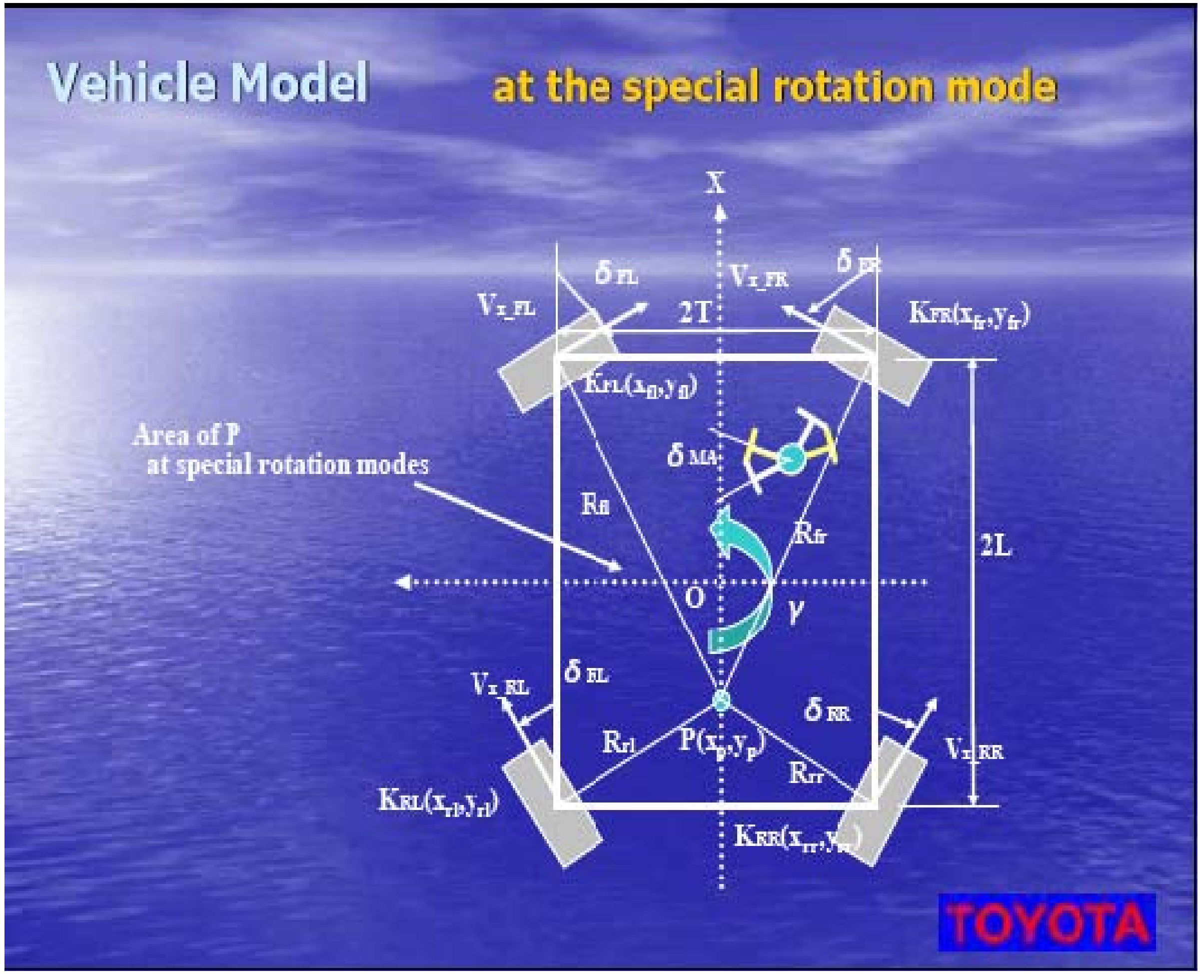
4wheel independent braking

By 'wheel-in-motor'

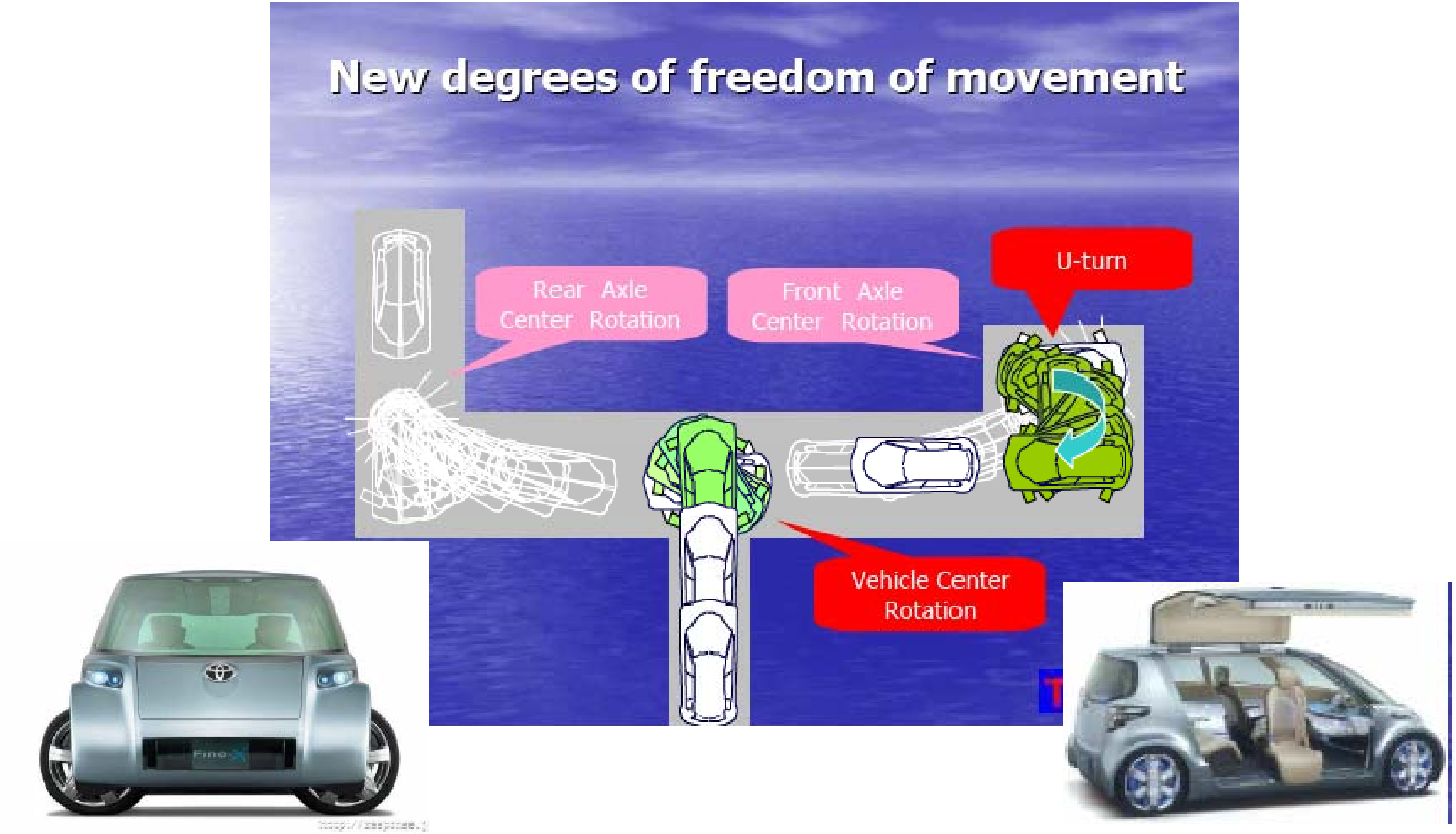
# TOYOTA Freer Movement Control System



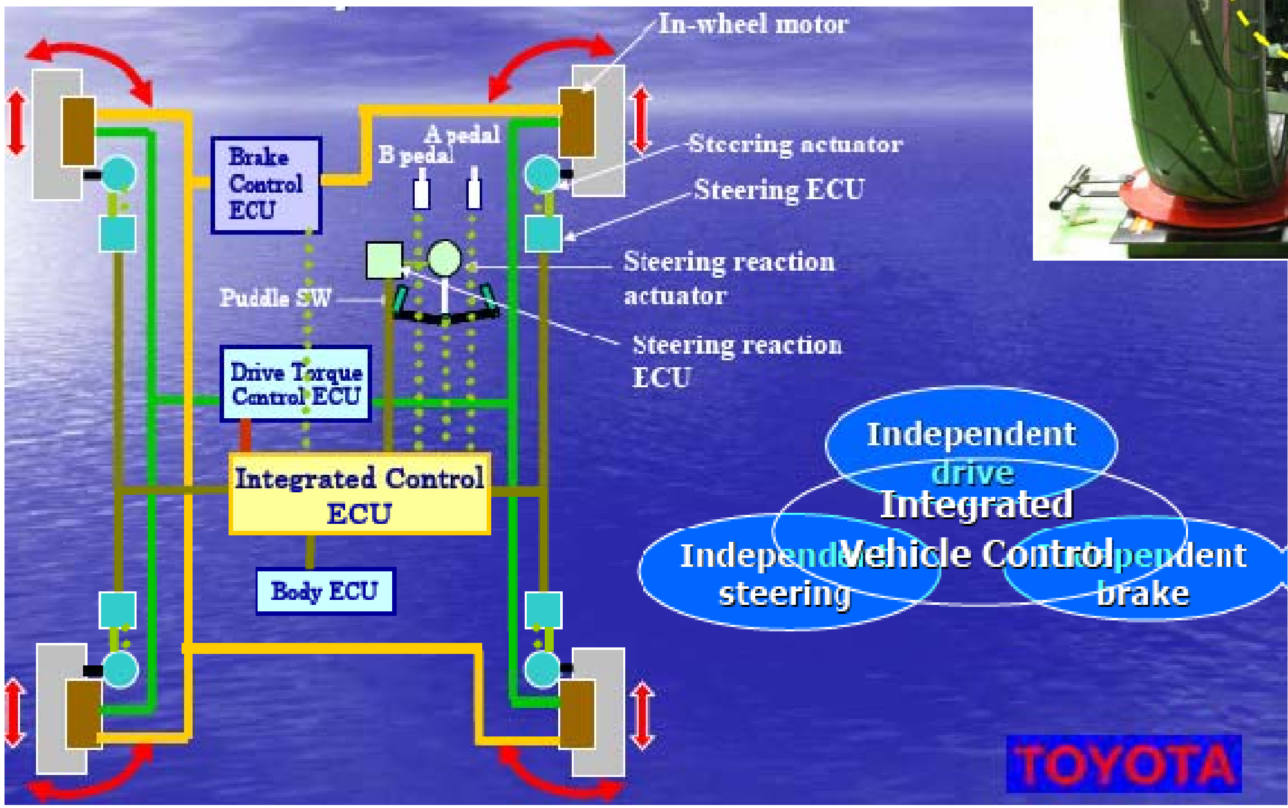
# TOYOTA Freer Movement Control System

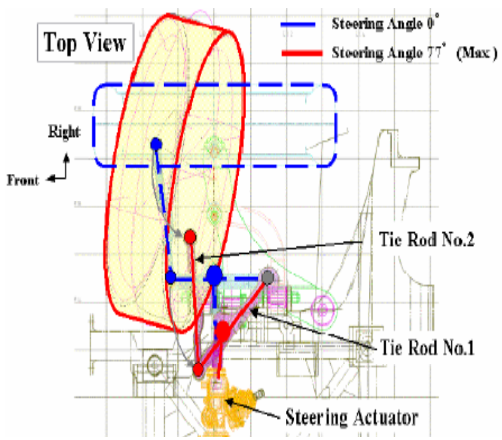



# TOYOTA Freer Movement Control System for Auto-Parking

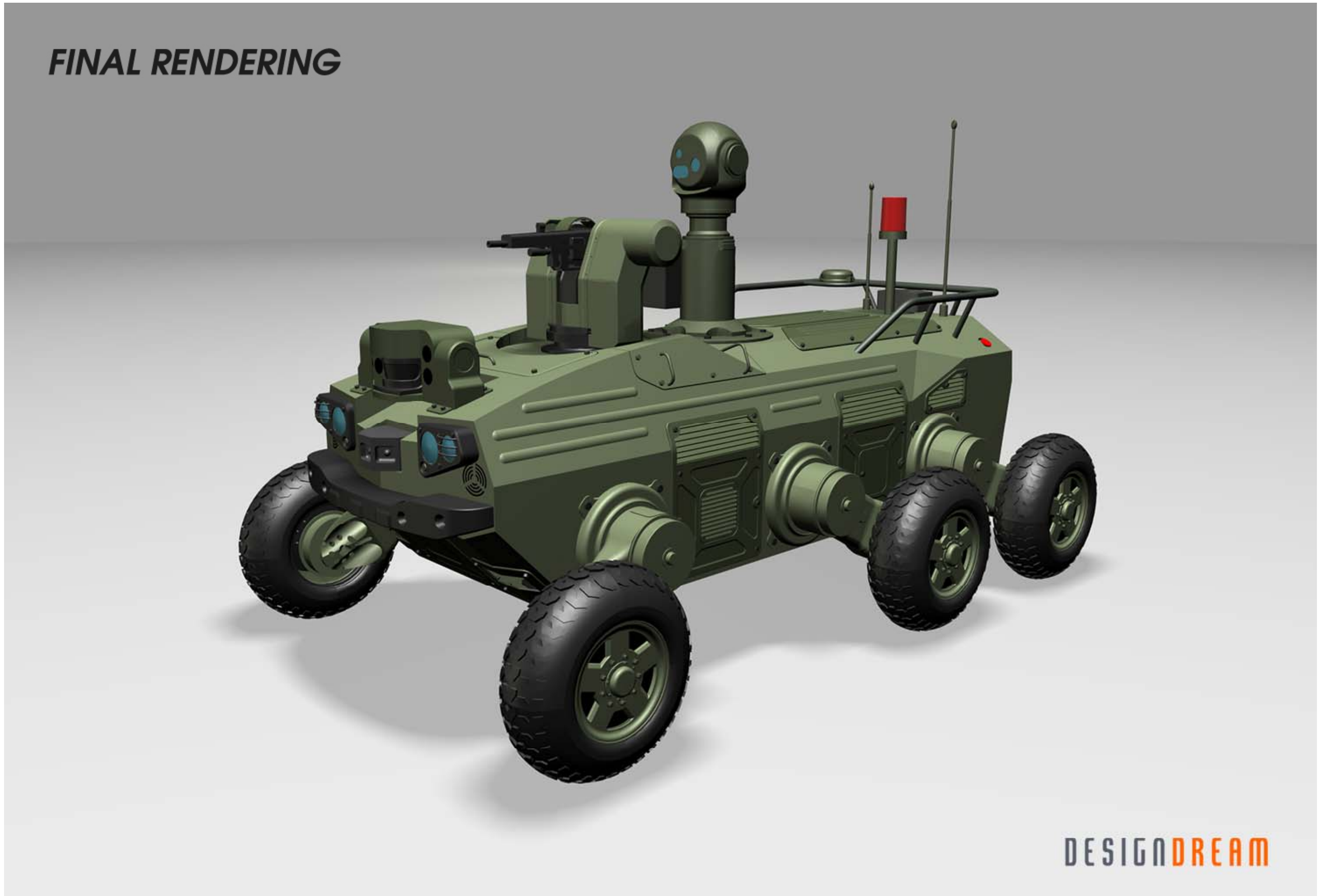


# TOYOTA Freer Movement Control System for Auto-Parking

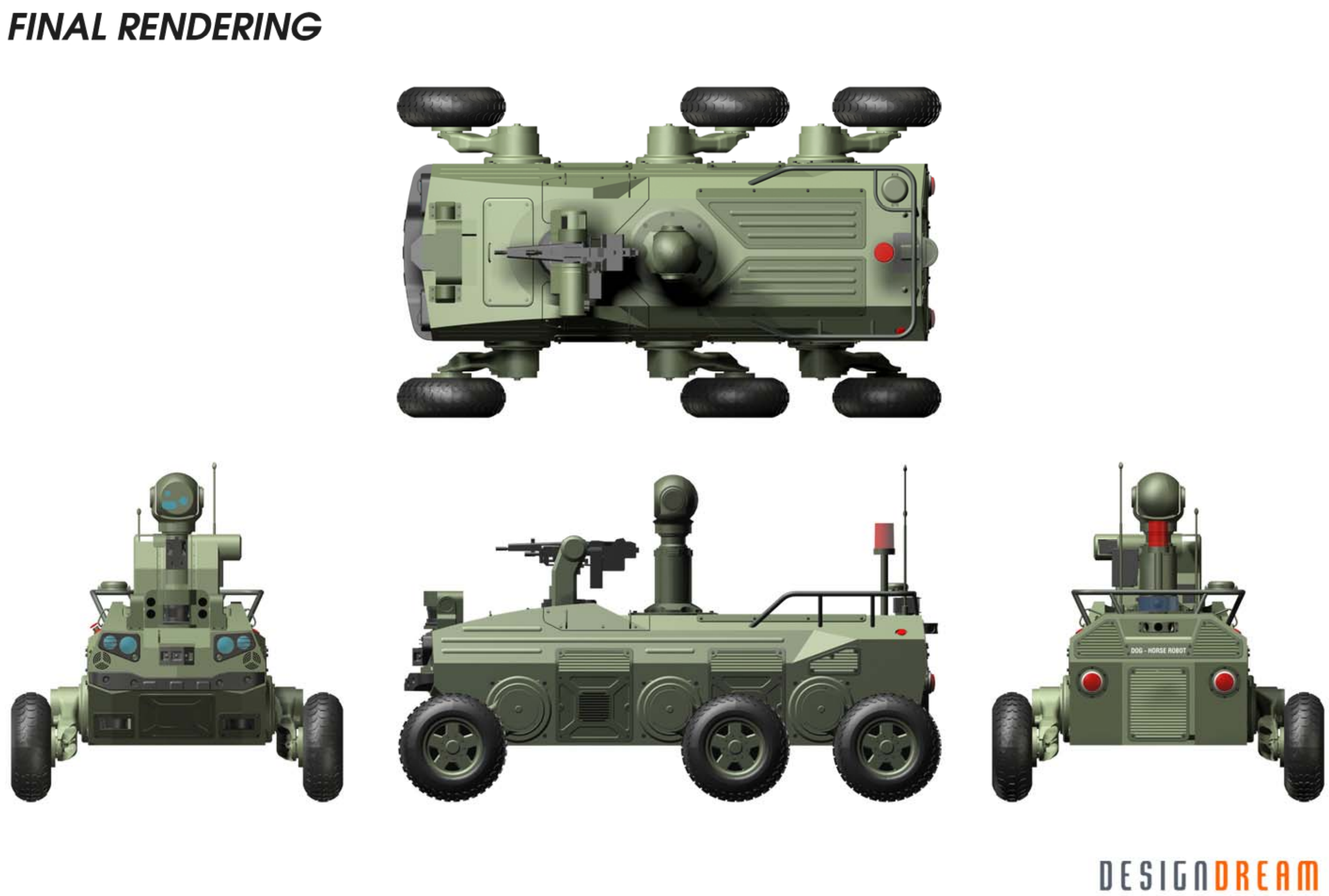


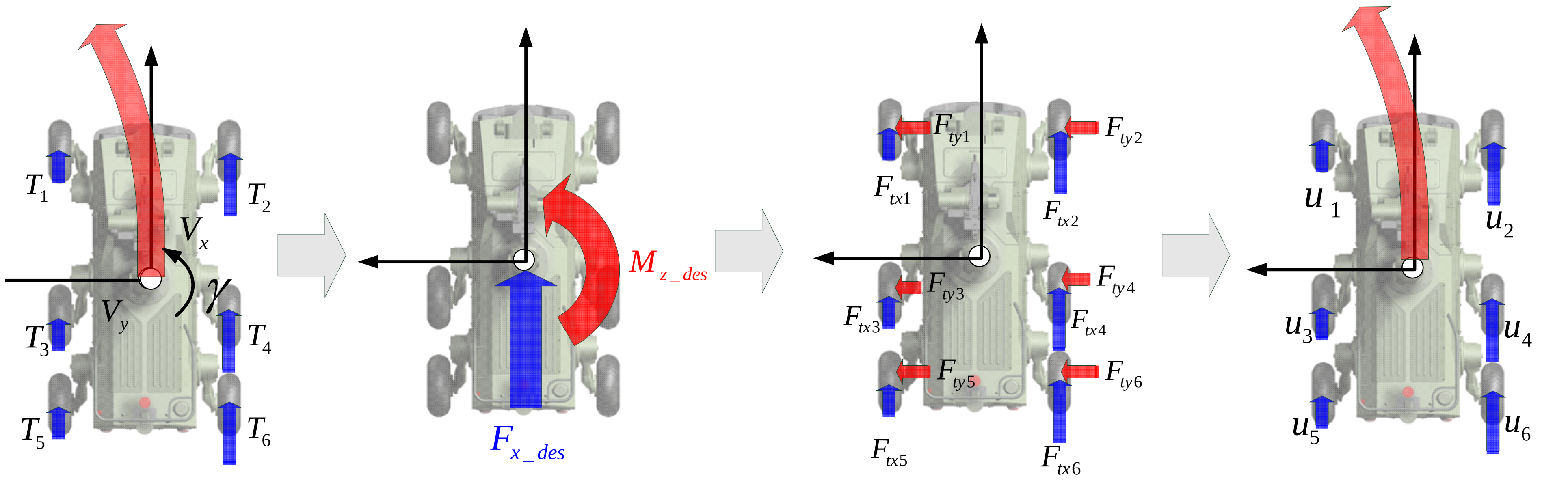
# Autonomous Robot Vehicle



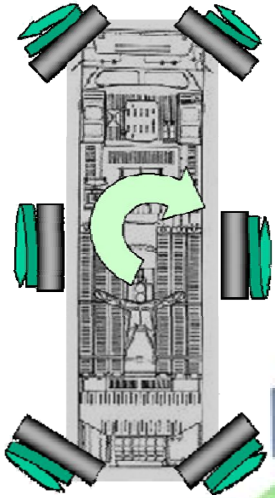
# Autonomous Robot Vehicle

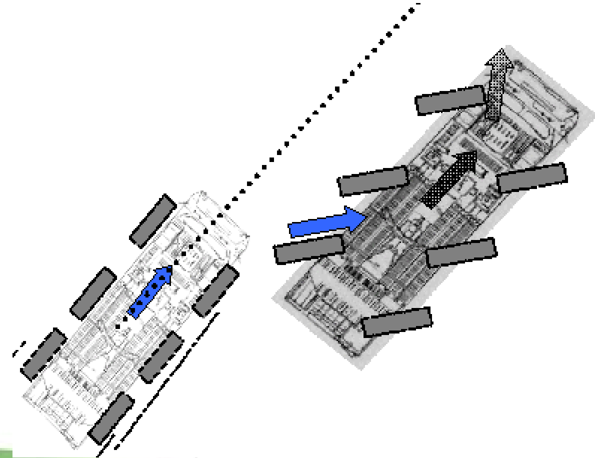


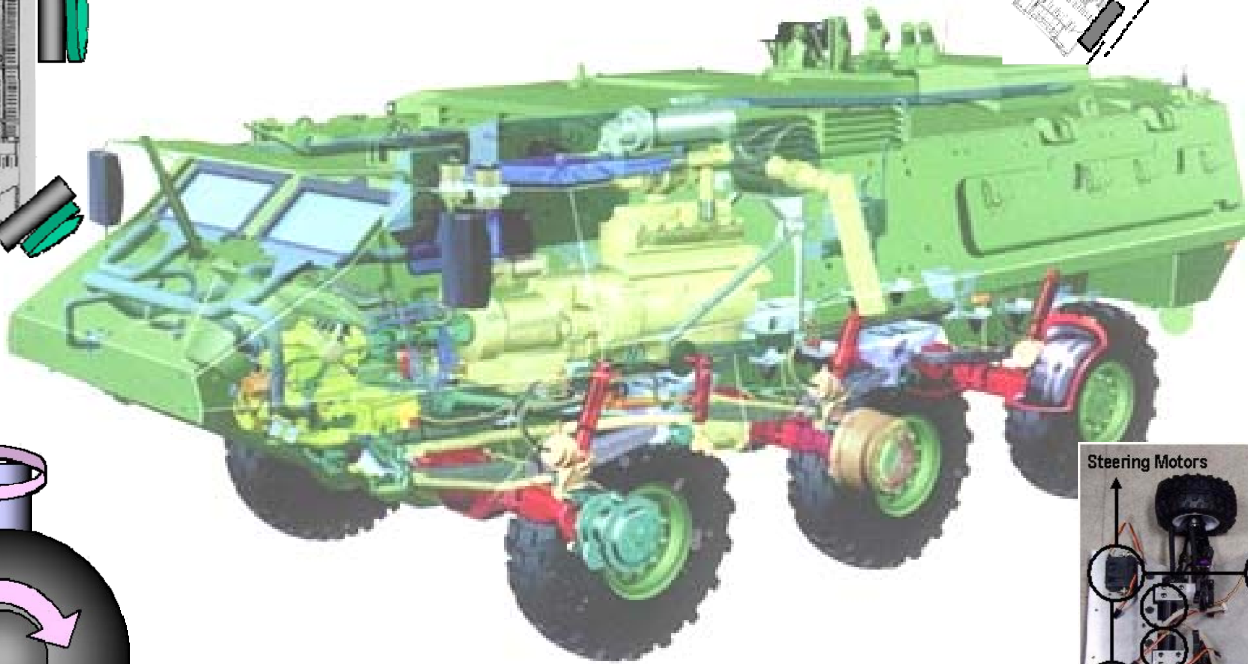
# 견마형 로봇 차량의 주행 제어 알고리즘

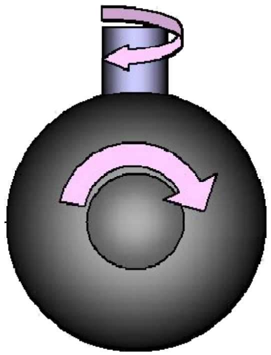


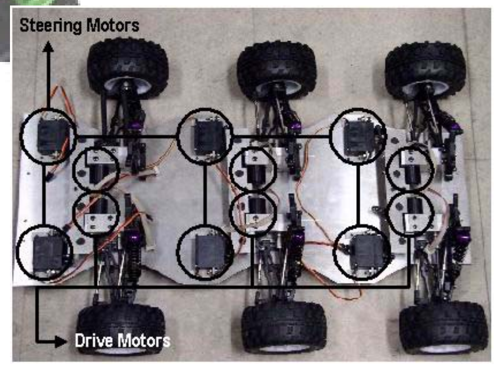
# 6WD6WS Vehicle



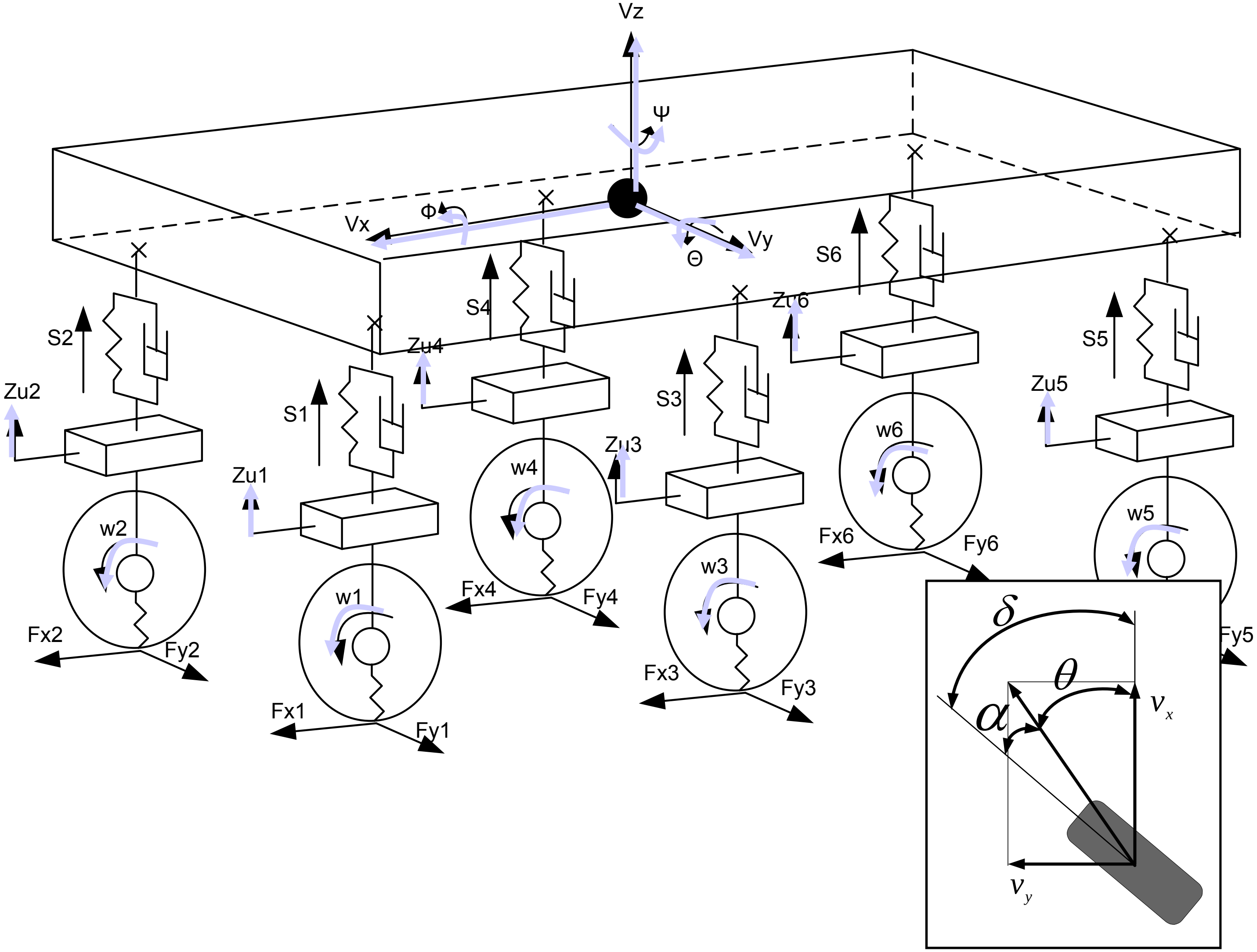






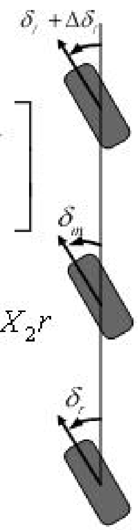


# 6WD6WS Vehicle

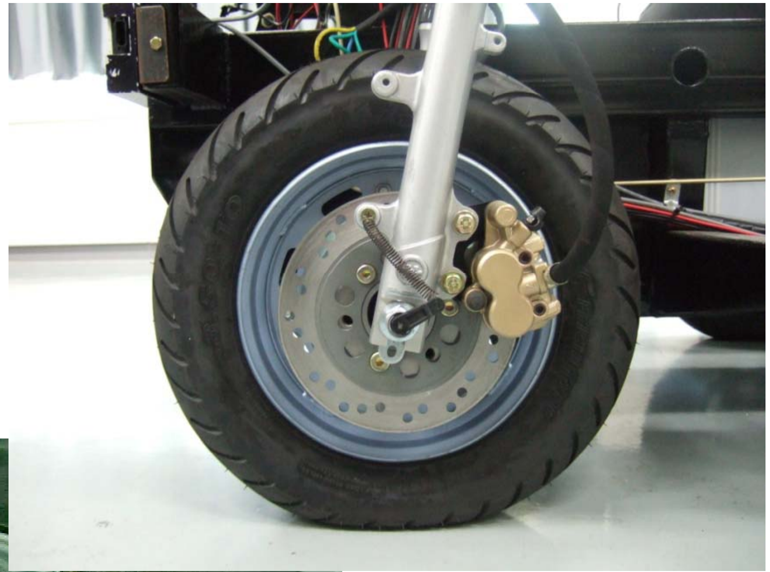



$$u = \begin{bmatrix} \Delta\delta_f \\ \delta_r \end{bmatrix}$$

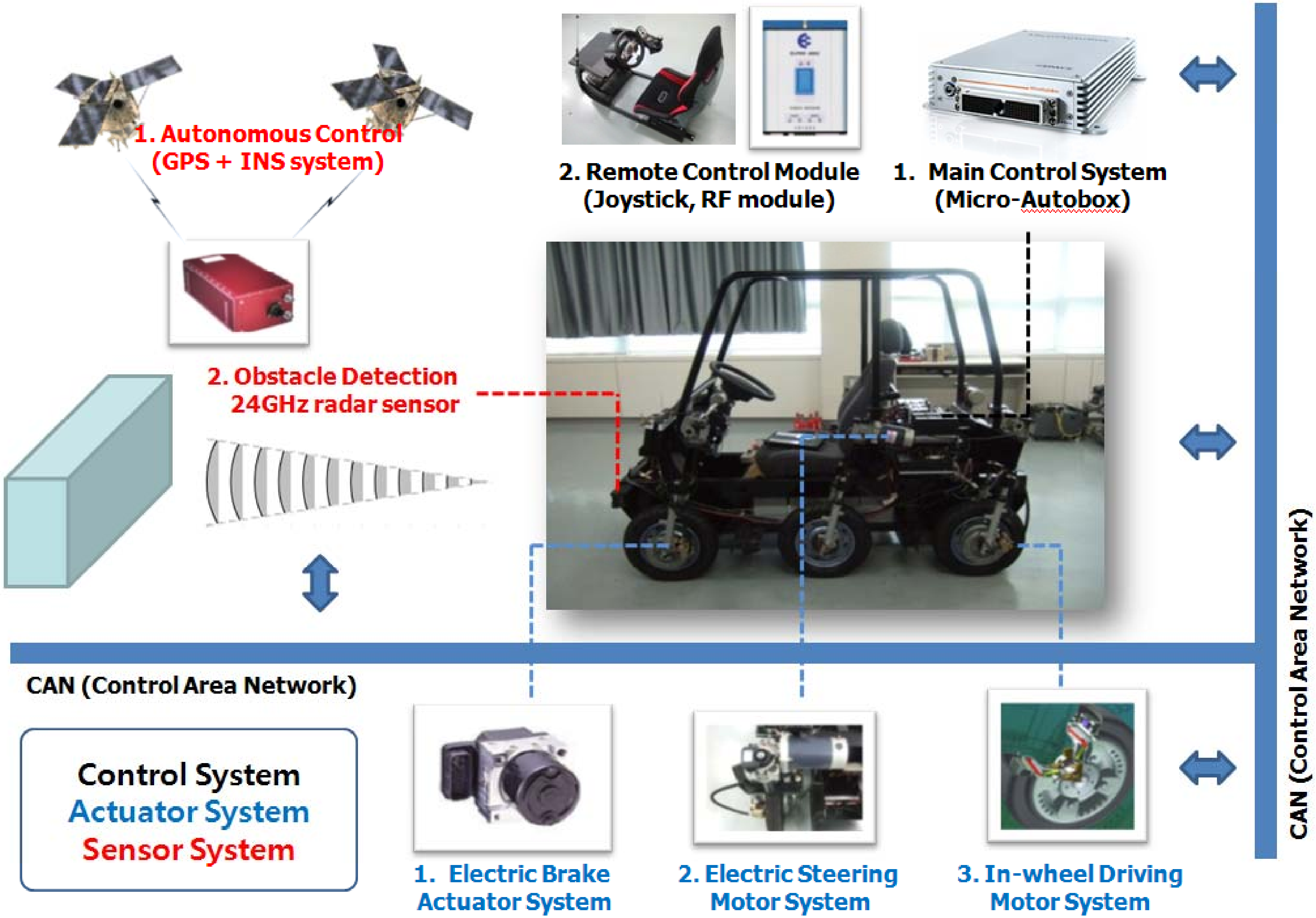
$$\delta_m = X_1\beta + X_2 r$$



# BLDC Wheel-in-Motor of 6WD6WS Vehicle



# Configuration of 6WD6WS Vehicle



# Sectional View of BLDC Motor

# Video of 6WD/6WS Vehicle equipped with Wheel-in Motor

**Parallel & Circular Turning**

평행_제자리선회.wmv

**Remote Control**

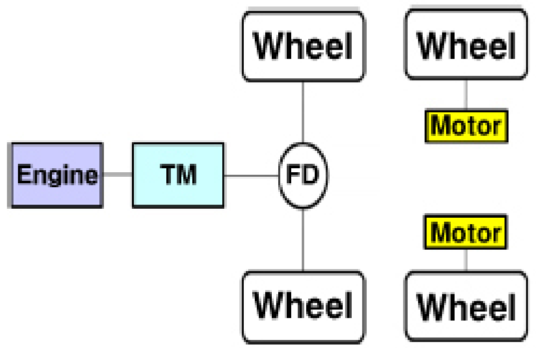
**Remote_general_recent.avi**

**Autonomous Driving**

**Autonomous_path_tracking.avi**

# Hybrid and Electrical Vehicles

- **Advantages**
  - Minimized both costs and technical issues
  - Even weight distribution
  - Simplest packaging
  - Improved vehicle chassis control




- **Targets**
  - To maintain or improve on **Euro 4 emissions**
  - To achieve a **30% overall reduction in $CO_2$** tail pipe emissions of the baseline vehicle operating with the same fuel, over the NEDC cycle as per EC/98/69 and EC/70/220 for vehicles less than 3500kg.
  - Equivalent fuel economy ≥ **60mpg=25.4kpl** (50% improvement in mpg on baseline vehicle)

# Hybrid and Electrical Vehicles

Skoda Fabia (Compact SUV)

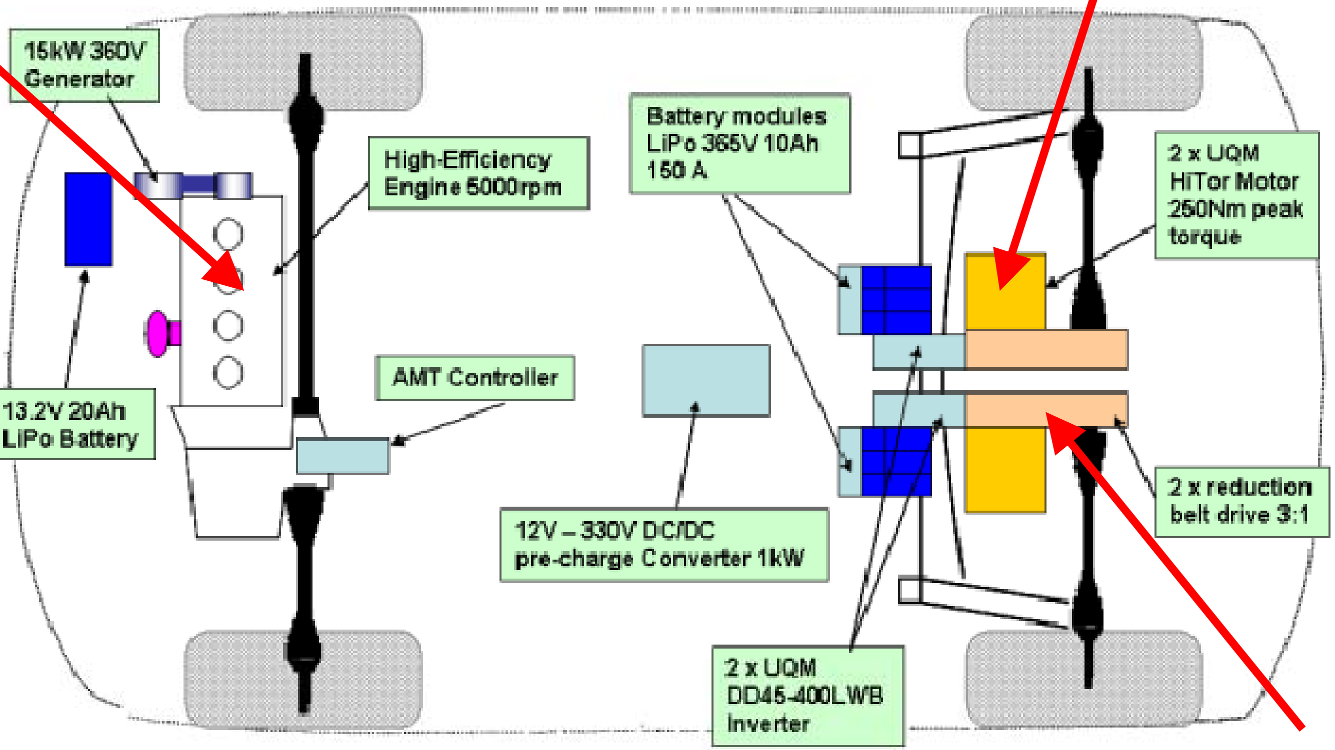


# Hybrid 4WD Vehicle Configuration

**Developed by MIRA (Skoda Fabia)**

**35 KW / 250 Nm Peak Torque**

**1400 cc 100 HP ICE**




**A total weight of around 150kg:**
**motors = 2x45kg, inverters=2x15kg, structure=30kg**

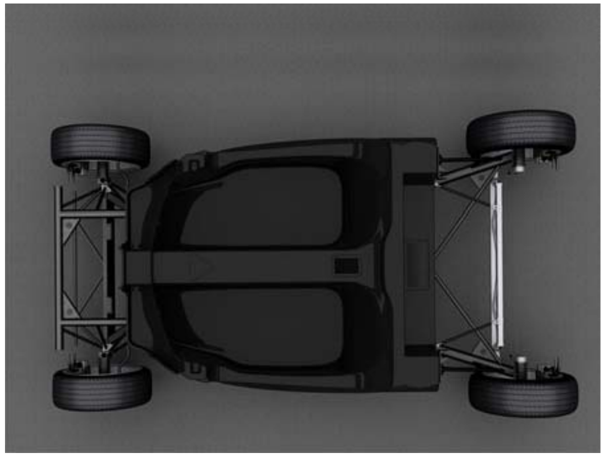
**3:1 reduction belt drive**
**➔ Peak torque = 750 Nm**

# 4 WD In-wheel Electric Vehicle

Michelin Active Wheel with in-wheel motor, suspension and brake system

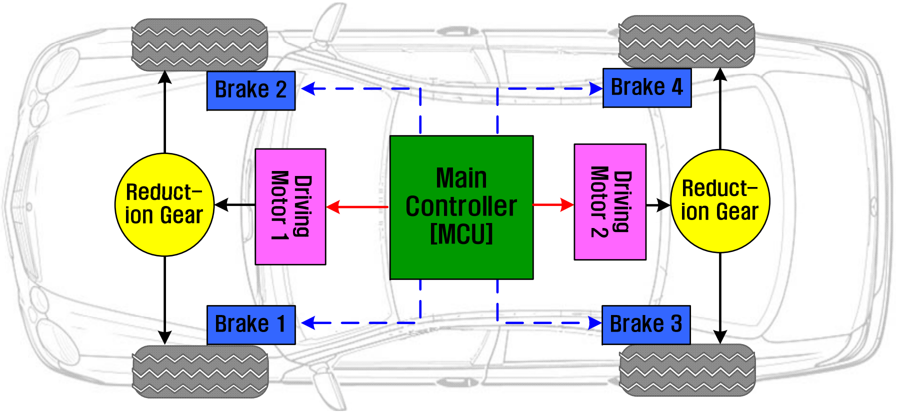

Electric vehicle equipped with Front two in-wheel motors

Electric vehicle equipped with four in-wheel motors

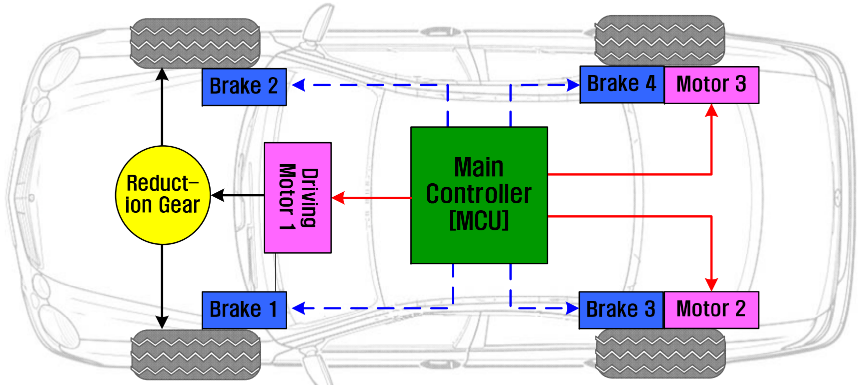


# 4 WD Electric Vehicle Combinations

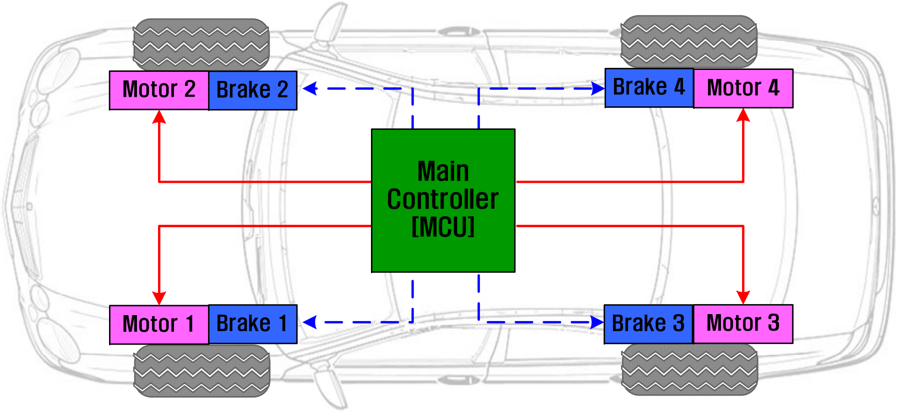
- Front/rear Two In-line Motors



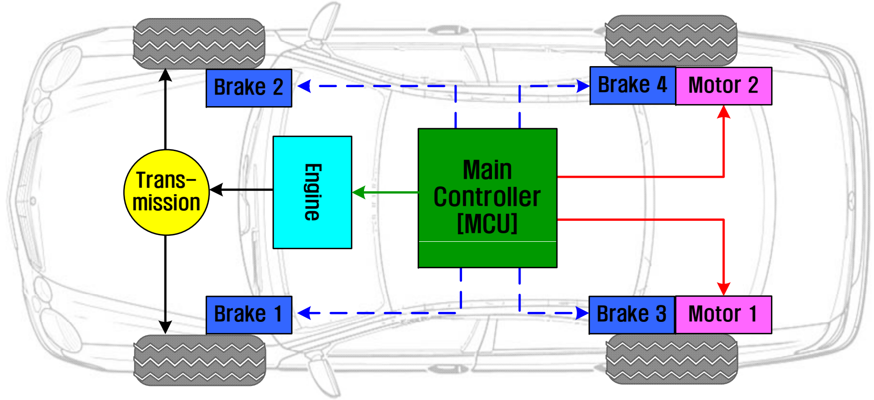

- Front In-line Motor/Rear In-wheel motors




- Four In-wheel Motors




- Front Engine Drive/Rear Two In-wheel Motors



# 6WD Skid Steering Vehicle

**Crusher**

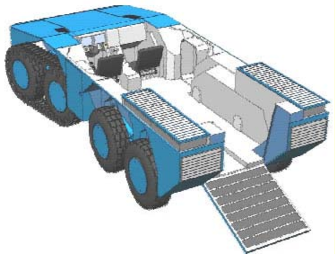

**Crusher highlights.wmv**

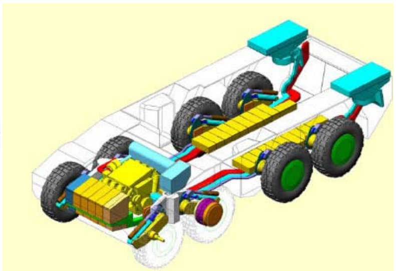
**APD**


**Autonomous Platform Demonstrator (APD) Overview.wmv**

# 8WD/4WS Vehicle Equipped with 8 In-wheel Motor

# AHED





AHED_8x8_vehicle_vedio.wmv

# Basic Elements

- Active Elements: OP Amp etc.
  (Has transistors/amplifiers that require active source of power to work)
- Passive Elements: Inductor, Resistor, Capacitor etc.
  (Simply respond to an applied voltage or current.)

- Current : the rate of flow of charge
- Charge : (electric charge) the integral of current with respect to time [C]

$$i = \frac{dq}{dt} \qquad [\text{ampere}] = \frac{[\text{coulomb}]}{[\text{sec}]}$$

- Voltage : electromotive force needed to produce a flow of current in a wire [V]
  Change in energy as the charge is passed through a component.
  [V] = [J/C]
- Power: product of voltage and current

  [W] = [J/Sec]

# Basic Elements - Resistance

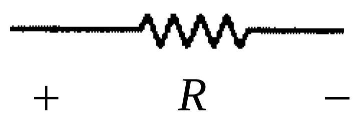
- Resistance : the change in voltage required to make a unit change in current.

Analogous to → Damping Element

$$R = \frac{Change\ \ in\ \ voltage}{Change\ \ in\ \ current} = \frac{[V]}{[A]} = [Ohm(\Omega)]$$

- Resistor

$$V_R = R \cdot i_R \qquad R = \frac{V_R}{i_R}$$



# Basic Elements - Capacitance

- Capacitance: the change in the quantity of electric charge required to make a unit change in voltage.

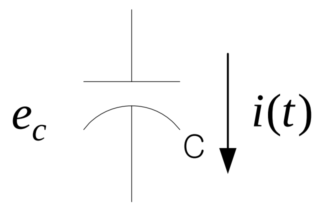
Analogous to → Spring Element (Stores Potential Energy)

$$C = \frac{[Coulomb]}{[V]} = [Farad\ (F)]$$

- Capacitor: two conductor separated by non-conducting medium.

$$i = dq/dt\ , \quad e_c = q/C \quad \rightarrow\ i = C\frac{de_c}{dt}\ , \quad de_c = \frac{1}{C} i\ dt$$

$$\therefore e_c(t) = \frac{1}{C}\int_0^t i\ dt + e_c(0)$$




$$I(s) = CsV(s)\ , \quad V(s) = \frac{1}{Cs} I(s)$$

# Basic Elements - Inductance

- Inductance: An electromotive force induced in a circuit, if the circuit lies in a time –varying magnetic field.

Analogous to → Inertia Element (Stores Kinetic Energy)

$$L = \frac{[V]}{[A/\sec]} = [Henry\ (H)]$$

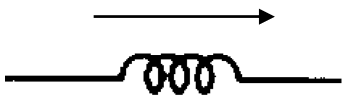
- Inductor:

$$e_L = L\frac{di_L}{dt}$$

$$\therefore\ i_L(t) = \frac{1}{L}\int_0^t e_L\ dt + i_L(0)$$

$$V(s) = LsI(s)$$

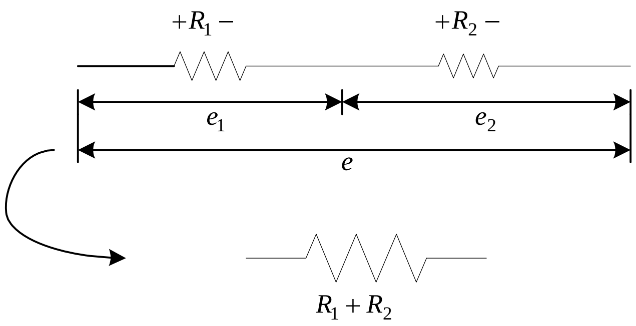
$$I(s) = \frac{1}{Ls}V(s)$$



$i(t)$

# Series & Parallel Resistance

- Series Resistance

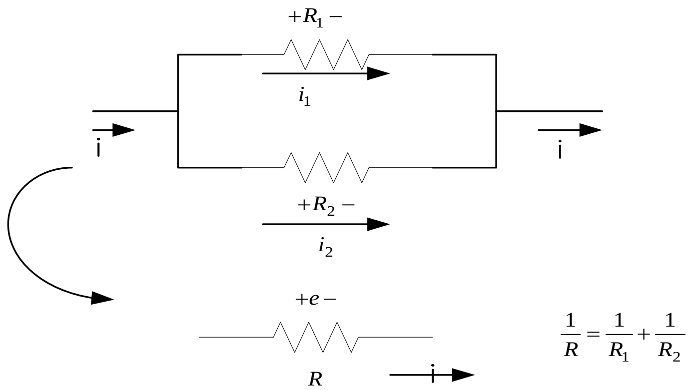



$$e_1 = iR_1, \quad e_2 = iR_2$$

$$e = e_1 + e_2 = i(R_1 + R_2)$$

Series/Parallel Capacitance?

- Parallel Resistance

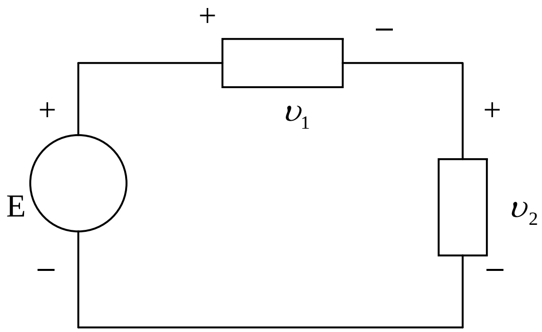



$$-e_1 + e_2 = 0 \quad \Rightarrow \quad e_1 = e_2$$

$$i = i_1 + i_2 = \frac{e_1}{R_1} + \frac{e_2}{R_2} = e\left(\frac{1}{R_1} + \frac{1}{R_2}\right) = \frac{e}{R}$$

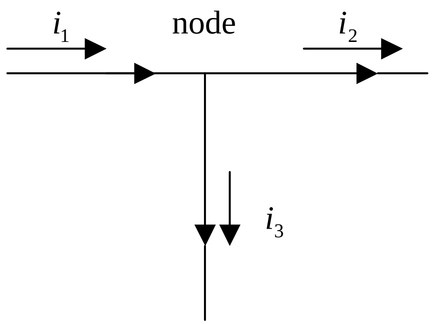
# Kirchhoff's laws

1. The algebraic sum of the potential difference around a closed path equals zero.




$$-\upsilon_1 - \upsilon_2 + E = 0$$

2. The algebraic sum of the currents entering (or leaving) a nod is equal to zero.

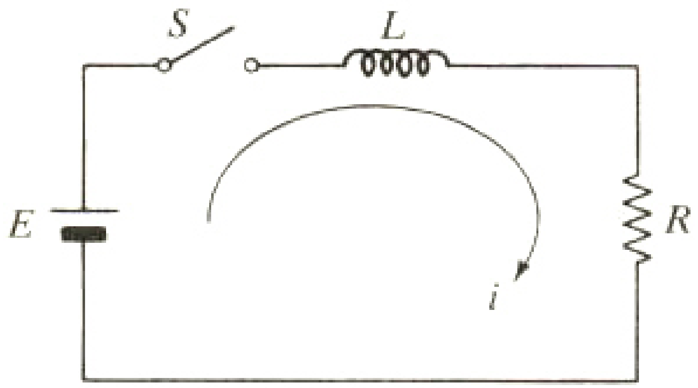



$$i_1 - i_2 - i_3 = 0$$

Current in = Current out

$$\rightarrow \quad i_1 = i_2 + i_3$$

# Mathematical Modeling of Electrical Systems




The switch S is closed at t=0

$$E - L\frac{di}{dt} - Ri = 0 \qquad or \qquad L\frac{di}{dt} + Ri = E$$

At the instant that switch S is closed,

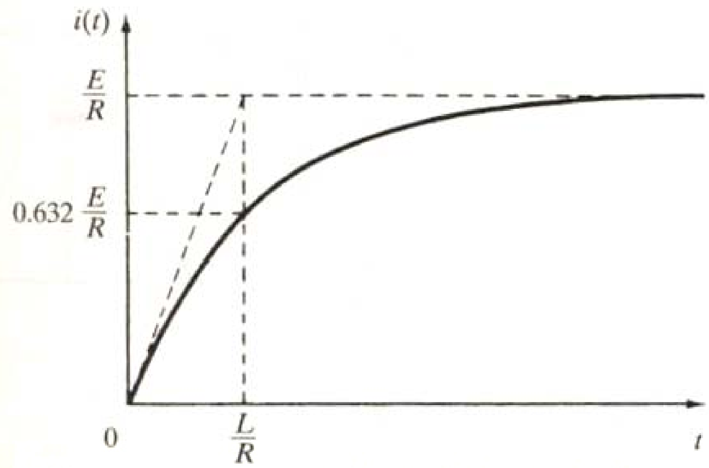
the current $i(0) = 0$

Laplace Transformation : $L\left[sI(s) - i(0)\right] + RI(s) = \frac{E}{s}$

$$i(0) = 0 \quad \rightarrow \quad (Ls+R)I(s) = \frac{E}{s}$$

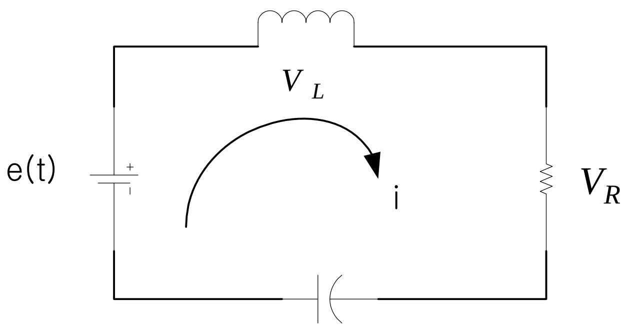
$$I(s) = \frac{E}{s(Ls+R)} = \frac{E}{R}\left[\frac{1}{s} - \frac{1}{s+(R/L)}\right]$$

$$\therefore \; i(t) = \frac{E}{R}\left[1 - e^{-(R/L)\,t}\right]$$



# Examples of Circuit Analysis

ex) R-L-C Circuit




$$-V_L - V_R - V_C + e(t) = 0$$

$$V_L = L\frac{di}{dt}, \quad V_R = iR, \quad V_c = \frac{1}{C}\int i\,dt + V_C(t)$$

$$\frac{dV_c}{dt} = \frac{1}{C}i$$

$$L\frac{di}{dt} + Ri = e(t) - V_C(t)$$

Laplace Transform, $$(Ls + R + \frac{1}{Cs})I(s) = E(s)$$

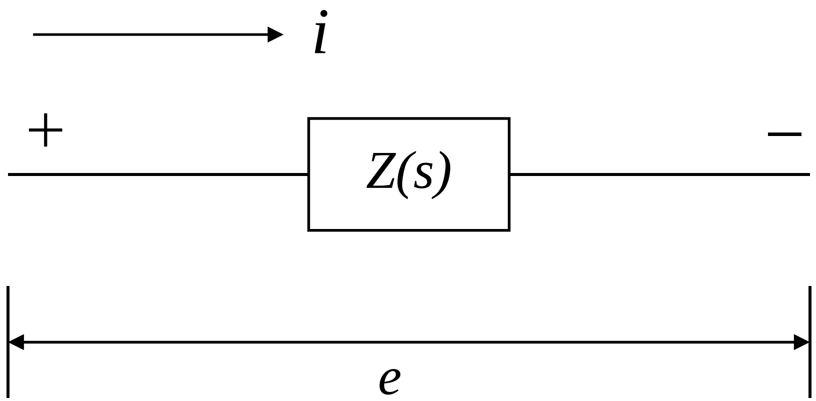
$$\frac{I(s)}{E(s)} = \frac{1}{(Ls + R + \frac{1}{Cs})}$$

$$V_o(s) = \frac{1}{Cs}I(s)$$

$$V_o(s) = \frac{\frac{1}{Cs}}{(Ls + R + \frac{1}{Cs})}E(s) = \frac{1}{(LCs^2 + RCs + 1)}E(s)$$

Step Response?

# Complex Impedance

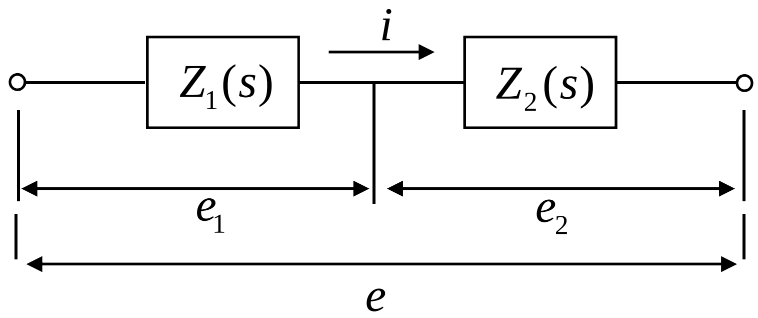



$$I(s) = \frac{E(s)}{Z(s)} \qquad E(s) = Z(s)I(s)$$

Z(s) : complex impedance

# Complex Impedance

The complex impedance **Z(s)** of a two-terminal circuit is : the ratio of **E(s)** to **I(s)**




$$Z(s) = \frac{E(s)}{I(s)}, \qquad E(s) = Z(s)I(s)$$

$$E_1(s) = Z_1(s)I(s), \qquad E_2(s) = Z_2(s)I(s)$$

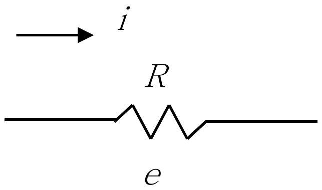
$$\begin{aligned} E(s) &= E_1(s) + E_2(s) \\ &= Z_1(s)I(s) + Z_2(s)I(s) \\ &= \left(Z_1(s) + Z_2(s)\right)I(s) \end{aligned}$$

Direct derivation of transfer function,

without writing differential equations first.

# Complex Impedance

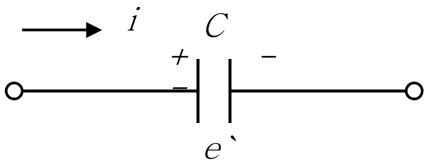
Resistance :




$$e = Ri, \quad E(s) = R\,I(s)$$

$$Z(s) = R$$

Capacitance :

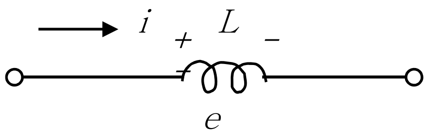



$$\frac{de}{dt} = \frac{1}{C} i$$

$$sE(s) = \frac{1}{C} I(s) \rightarrow E(s) = \frac{1}{Cs} I(s)$$

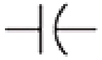
$$\therefore Z(s) = \frac{1}{Cs}$$

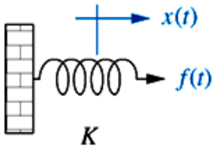
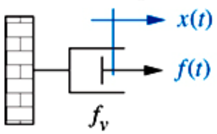
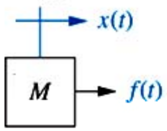
Inductance :




$$e = L\frac{di}{dt}, \qquad E(s) = L\,s\,I(s)$$

$$\therefore Z(s) = Ls$$

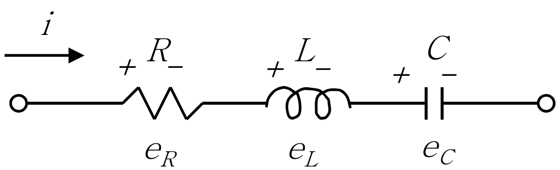
| Component | Voltage-current | Current-voltage | Voltage-charge | Impedance $Z(s) = V(s)/I(s)$ | Admittance $Y(s) = I(s)/V(s)$ |
|---|---|---|---|---|---|
|  Capacitor | $v(t) = \frac{1}{C}\int_0^t i(\tau)d\tau$ | $i(t) = C\frac{dv(t)}{dt}$ | $v(t) = \frac{1}{C}q(t)$ | $\frac{1}{Cs}$ | $Cs$ |
|  Resistor | $v(t) = Ri(t)$ | $i(t) = \frac{1}{R}v(t)$ | $v(t) = R\frac{dq(t)}{dt}$ | $R$ | $\frac{1}{R} = G$ |
|  Inductor | $v(t) = L\frac{di(t)}{dt}$ | $i(t) = \frac{1}{L}\int_0^t v(\tau)\, d\tau$ | $v(t) = L\frac{d^2q(t)}{dt^2}$ | $Ls$ | $\frac{1}{Ls}$ |

| Component | Force-velocity | Force-displacement | Impedence $Z_M(s) = F(s)/X(s)$ |
|---|---|---|---|
| Spring   | $f(t) = K\int_0^t v(\tau)d\tau$ | $f(t) = Kx(t)$ | $K$ |
| Viscous damper   | $f(t) = f_v v(t)$ | $f(t) = f_v\frac{dx(t)}{dt}$ | $f_v s$ |
| Mass   | $f(t) = M\frac{dv(t)}{dt}$ | $f(t) = M\frac{d^2x(t)}{dt^2}$ | $Ms^2$ |

# Examples of Complex Impedance

## Series Impedances

ex1)



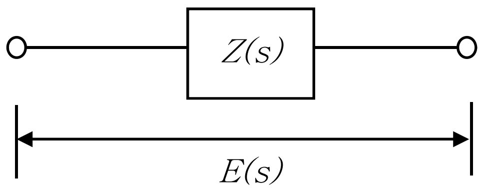

$$e_R = iR, \quad e_L = L\frac{di}{dt}, \quad \frac{de_C}{dt} = \frac{1}{C}i$$

$$e = e_R + e_L + e_C$$

$$E(s) = E_R(s) + E_L(s) + E_C(s)$$

$$= RI(s) + LsI(s) + \frac{1}{cS}I(s)$$

$$= \left(R + Ls + \frac{1}{Cs}\right)I(s)$$

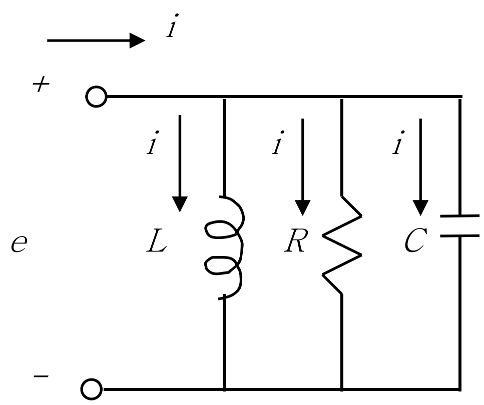



$$\therefore Z(s) = R + Ls + \frac{1}{Cs} = Z_R(s) + Z_L(s) + Z_C(s)$$

# Examples of Complex Impedance

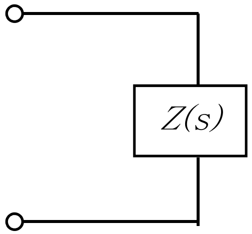
## Parallel Impedances

ex2)




$$i = i_L + i_R + i_C \qquad E(s) = Z(s)I(s)$$

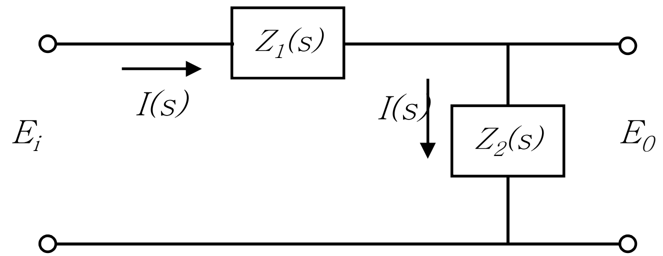
$$\begin{aligned} I(s) &= I_L(s) + I_R(s) + I_C(s) \\ &= \frac{E(s)}{Z_L(s)} + \frac{E(s)}{Z_R(s)} + \frac{E(s)}{Z_C(s)} \\ &= \left( \frac{1}{Z_L(s)} + \frac{1}{Z_R(s)} + \frac{1}{Z_C(s)} \right) E(s) \\ &= \frac{1}{Z(s)} E(s) \end{aligned}$$




$$\therefore Z(s) = \frac{1}{\dfrac{1}{Z_R(s)} + \dfrac{1}{Z_L(s)} + \dfrac{1}{Z_C(s)}} = \frac{1}{\dfrac{1}{Ls} + \dfrac{1}{R} + Cs}$$

# Examples of Complex Impedance

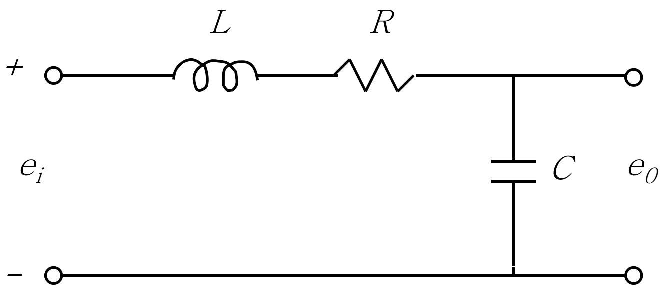
Deriving transfer functions of Electrical circuits by the use of complex impedances.




$$E_i(s) = Z_1(s)I(s) + Z_2(s)I(s)\,, \qquad E_o(s) = Z_2(s)I(s)$$

$$\frac{E_o(s)}{E_i(s)} = \frac{Z_2(s)}{Z_1(s) + Z_2(s)}$$

ex)



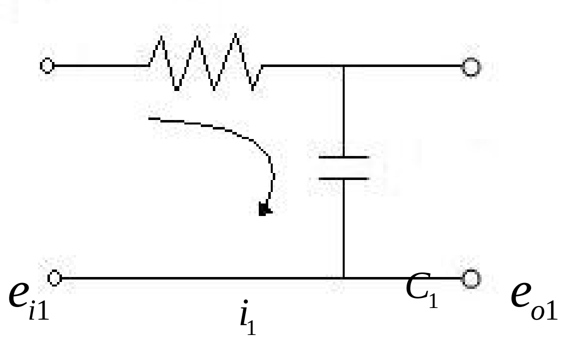

$$\frac{E_o(s)}{E_i(s)} = \frac{Z_2(s)}{Z_1(s) + Z_2(s)}$$

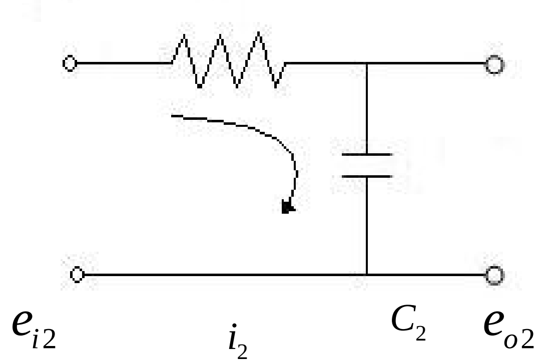
$$Z_1(s) = L\,s + R, \quad Z_2(s) = \frac{1}{Cs}$$

$$\frac{E_o(s)}{E_i(s)} = \frac{\frac{1}{Cs}}{Ls + R + \frac{1}{Cs}} = \frac{1}{LCs^2 + RCs + 1}$$

# Transfer Functions of Cascaded Elements

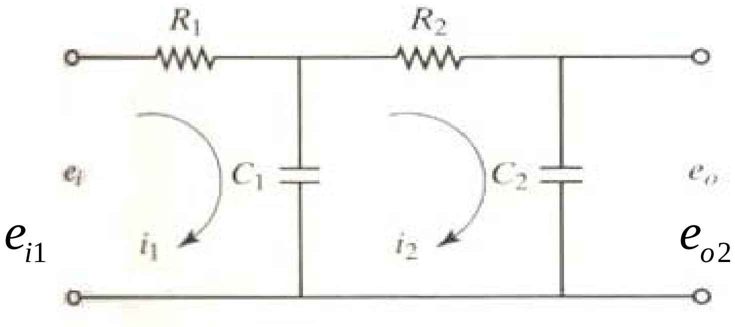
Consider two RC circuits



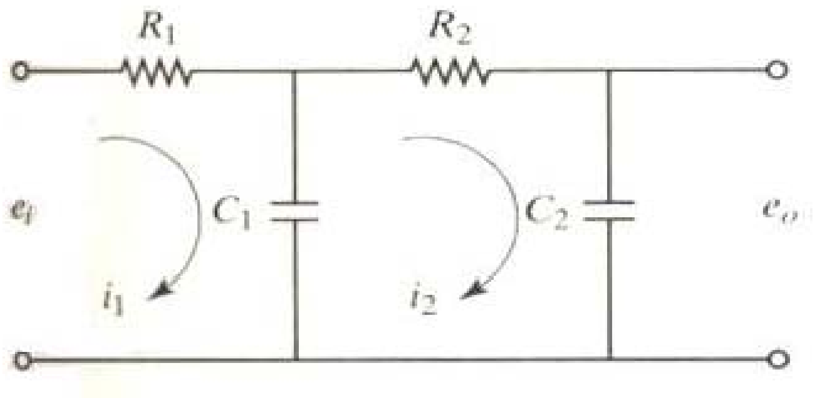

$$\frac{E_{o1}(s)}{E_{i1}(s)} = \frac{1}{R_1 C_1 s + 1} = G_1(s)$$

$$\frac{E_{o2}(s)}{E_{i2}(s)} = \frac{1}{R_2 C_2 s + 1} = G_2(s)$$




$$\frac{E_{o2}(s)}{E_{i1}(s)} = ?$$

# Transfer Functions of Cascaded Elements
# Loading Effect



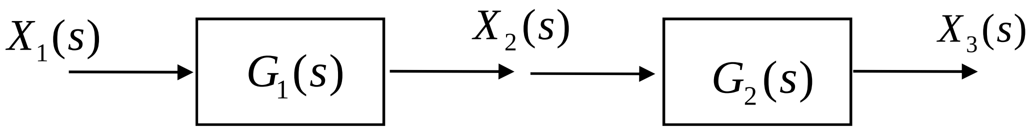

$$E_i(s) = \frac{1}{C_1 s}\left[I_1(s) - I_2(s)\right] + R_1 I_1(s), \quad \frac{1}{C_1 s}\left[I_2(s) - I_1(s)\right] + R_2 I_2(s) + \frac{1}{C_2 s} I_2(s) = 0, \quad E_o(s) = \frac{1}{C_2 s} I_2(s)$$

$$T.F \ : \frac{E_o(s)}{E_i(s)} = \frac{1}{(R_1 C_1 s + 1)(R_2 C_2 s + 1) + R_1 C_2 s} \neq \frac{1}{(R_1 C_1 s + 1)(R_2 C_2 s + 1)}$$

$$\therefore \ \frac{E_o(s)}{E_i(s)} \neq \frac{E_{o1}(s)}{E_{i1}(s)} \cdot \frac{E_{o2}(s)}{E_{i2}(s)} \longrightarrow \text{Loading effect}$$

# Transfer Functions of Cascade Elements

## Input Impedance, Output Impedance



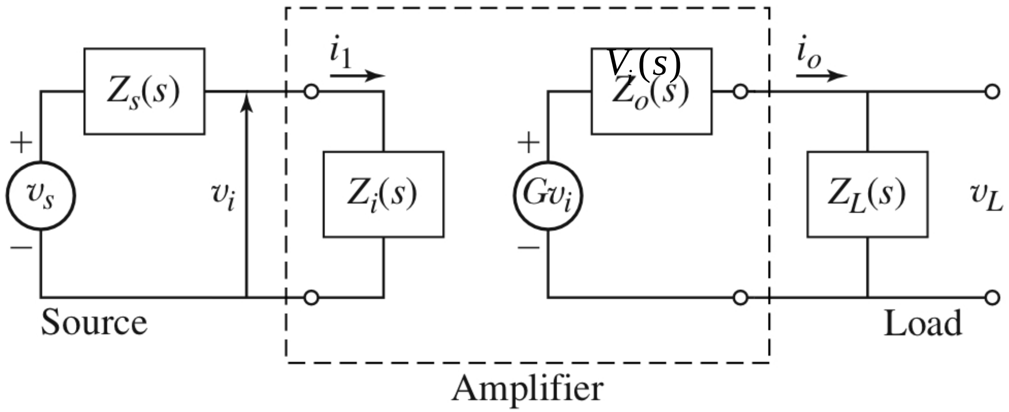

$$G(s) = \frac{X_3(s)}{X_1(s)} = \frac{X_2(s)}{X_1(s)} \cdot \frac{X_3(s)}{X_2(s)} = G_1(s)G_2(s)$$

If the "input Impedance" of the second element is infinite, the output of the first element is not affected by connecting it to the second element.

Then, $G(s) = G_1(s)G_2(s)$

# Transfer Functions of Cascade Elements

## Isolating Amplifier




This amplifier circuit has to

1. Not affect the behavior of the source circuit.
2. Not be affected by the loading circuit.

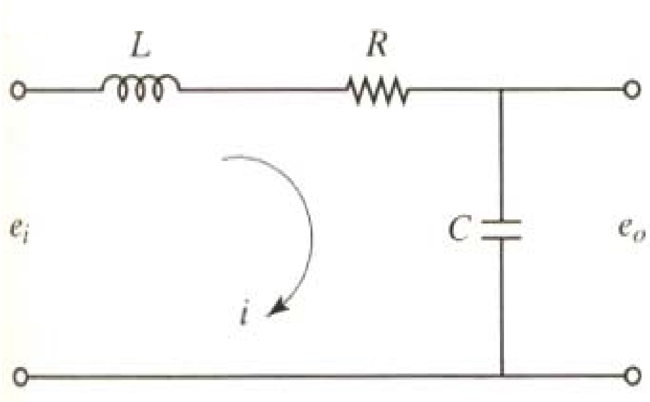
$$V_i(s) = \frac{Z_i(s)}{Z_i(s) + Z_s(s)} V_s(s) \approx V_s(s)$$

This isolating amplifier circuit has to have

1. a very high input impedance,
2. very low output impedance

$$V_L(s) = Z_L(s) I_o(s) = \frac{Z_L(s)}{Z_o(s) + Z_L(s)} G V_o(s) \approx G V_o(s)$$

# State-Space Mathematical Modeling of Electrical Systems




By Kirchhoff's voltage law

$$L\frac{di}{dt}+Ri+v_c=e_i\,,\qquad \frac{dv_c}{dt}=\frac{1}{C}i,\qquad e_o=v_c$$

Assume, initial condition is 0,

$$LsI(s)+RI(s)+V_c(s)=E_i(s),\qquad V_c(s)=\frac{1}{Cs}I(s)$$

$$T.F\ :\ \frac{E_o(s)}{E_i(s)}=\frac{1}{LCs^2+RCs+1}$$

# State-Space Mathematical Modeling of Electrical Systems

Differential equation :
$$\ddot{e}_o + \frac{R}{L}\dot{e}_o + \frac{1}{LC}e_o = \frac{1}{LC}e_i$$

State variable :
$$x_1 = e_o\,, \qquad x_2 = \dot{e}_o$$

Input and output :
$$u = e_i\,, \qquad y = e_o = x_1$$

State-space equation :

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\dfrac{1}{LC} & -\dfrac{R}{L} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \dfrac{1}{LC} \end{bmatrix} u, \qquad y = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$