# Total Sliding Mode Position Control of a Linear Variable Reluctance Motor

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- Structure and Principle of Linear Variable Reluctance (LVR) Motor
- Position Control
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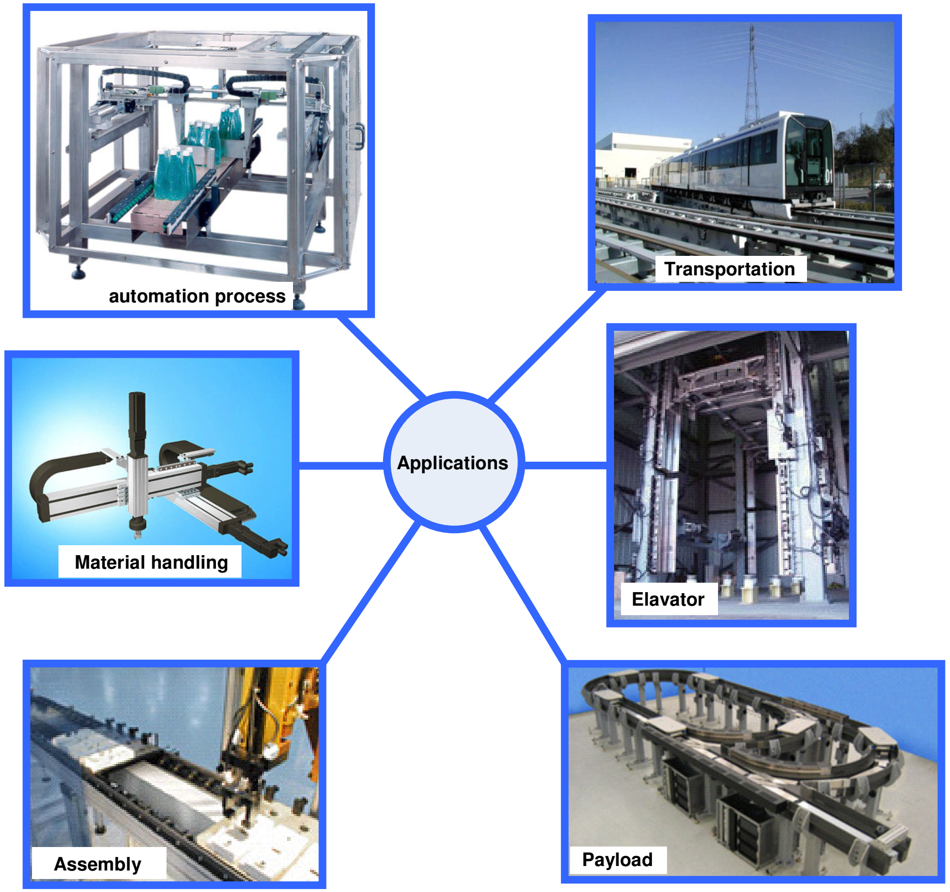
# Introduction

➢ **Applications of linear motion**



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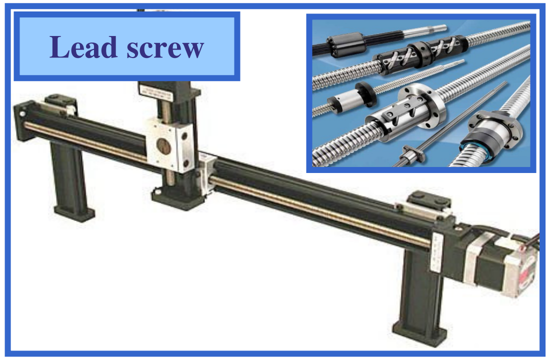
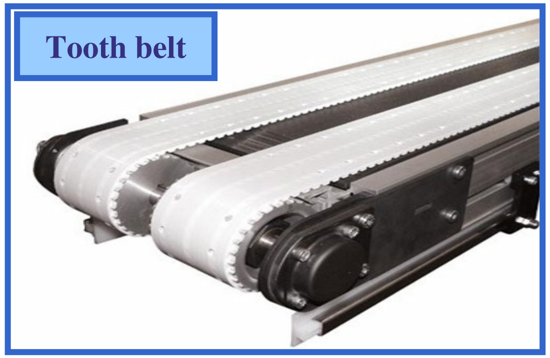
# Introduction

- Technologies for linear motion
  - Rotary motors with mechanical transmissions




## Advantages

**Simplicity for implementation, lower cost, more widely use**

## Disadvantages

**Mechanical transmission losses, high maintenance, mechanical limitations on acceleration and velocity, limited accuracy**

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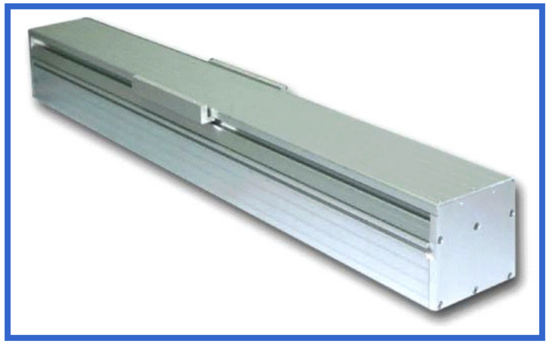
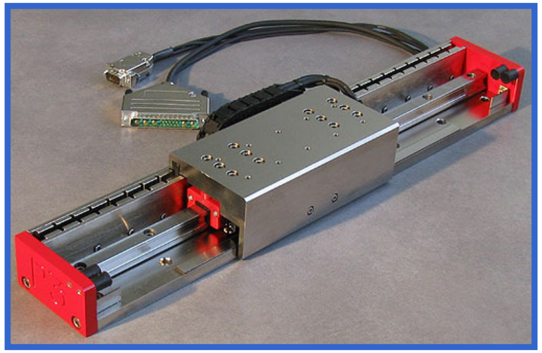
# Introduction

- Technologies for linear motion
  - Linear motors (direct drive): permanent magnet, reluctance, induction, DC





## Advantages

**Less friction, higher accuracy, no backlash, low maintenance, longer lifetime**

## Disadvantages

**Higher cost, high maintenance (LPM)**

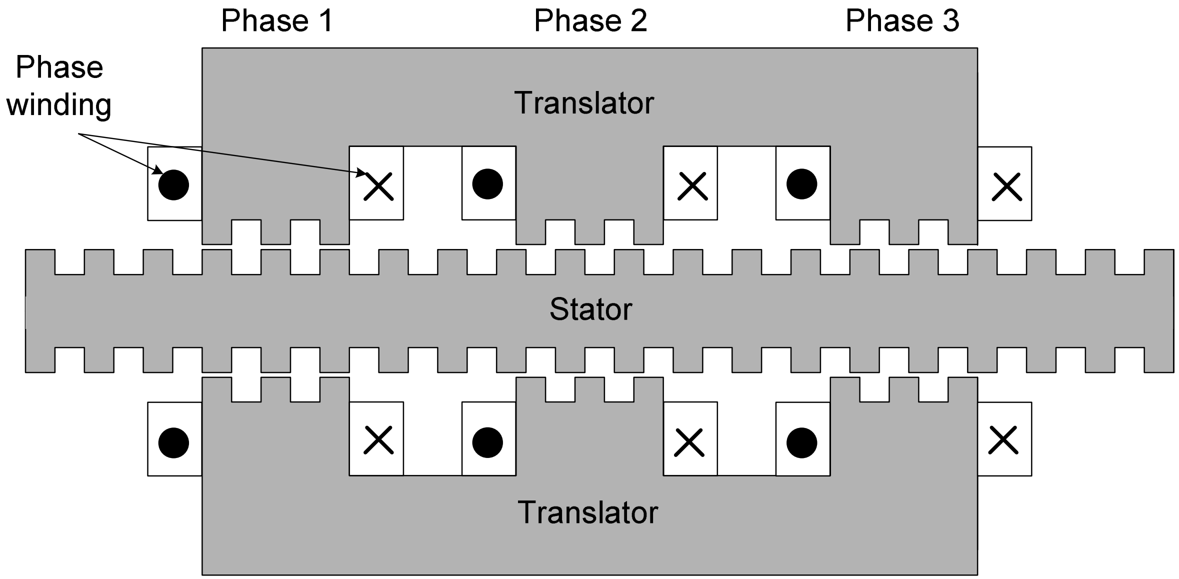
# Introduction

➢ Goals of paper

1. Develop a simple position control with good performance for LVR motor

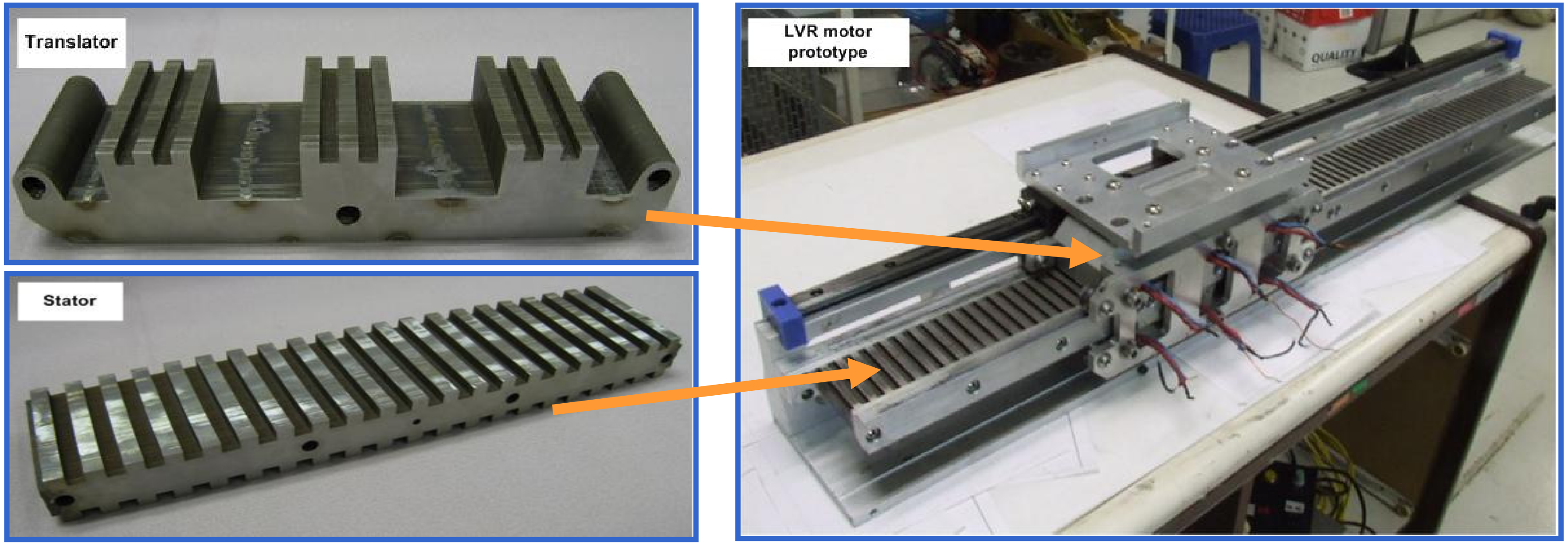
2. Implement the developed position control, which is based on a simplified sinusoidal flux model for LVR motor

# Structure and Principle of LVR Motor




- Two E-cores moving along the stator
- Motor windings are installed on each side of the E-cores
- Strong magnetic coupling between phases
- Symmetric structure with zero normal force when balanced

# Structure and Principle of LVR Motor




**Advantages:**

Simple structure, compactness, low cost (no permanent magnet)

# Structure and Principle of LVR Motor

- **Phase voltage equations of the LVR motor in the dq0 domain**

$$u_d = Ri_d - \alpha L_q i_q \frac{dx}{dt} + L_d \frac{di_d}{dt}$$

$$u_q = Ri_q + \alpha L_d i_d \frac{dx}{dt} + L_q \frac{di_q}{dt}$$

$$u_0 = Ri_0$$

- **Force function of the LVR motor**

$$f(i_q, i_d) = \alpha \left( L_d - L_q \right) i_q i_d$$

$$\alpha = \frac{\pi}{p_t}$$

# Structure and Principle of LVR Motor

- **Mechanical dynamic equation of the LVR motor**

$$F = M\ddot{x} + B\dot{x} + F_L$$

$M$ : **Moving mass**

$B$ : **Viscous friction coefficient**

$F_L$ : **External force**

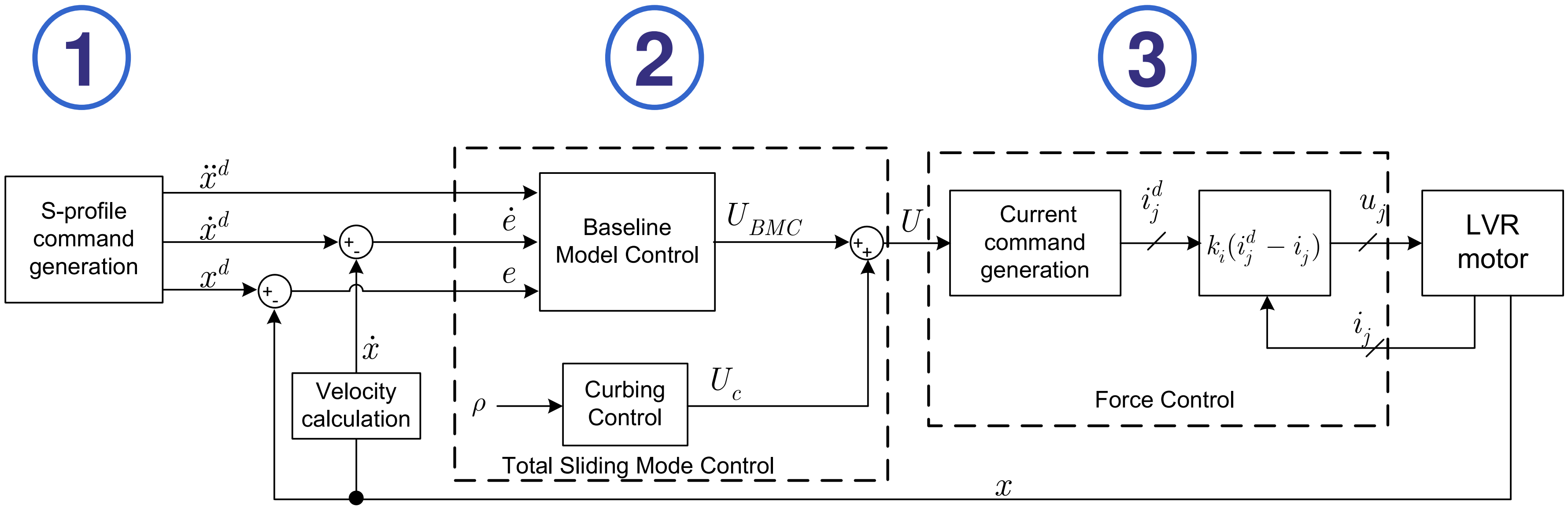
# Position Control

- Design for high precision position control for manufacturing automation applications

- Use the dq0 theory of classical synchronous reluctance motors
  - Sinusoidal reluctance/inductance approximation

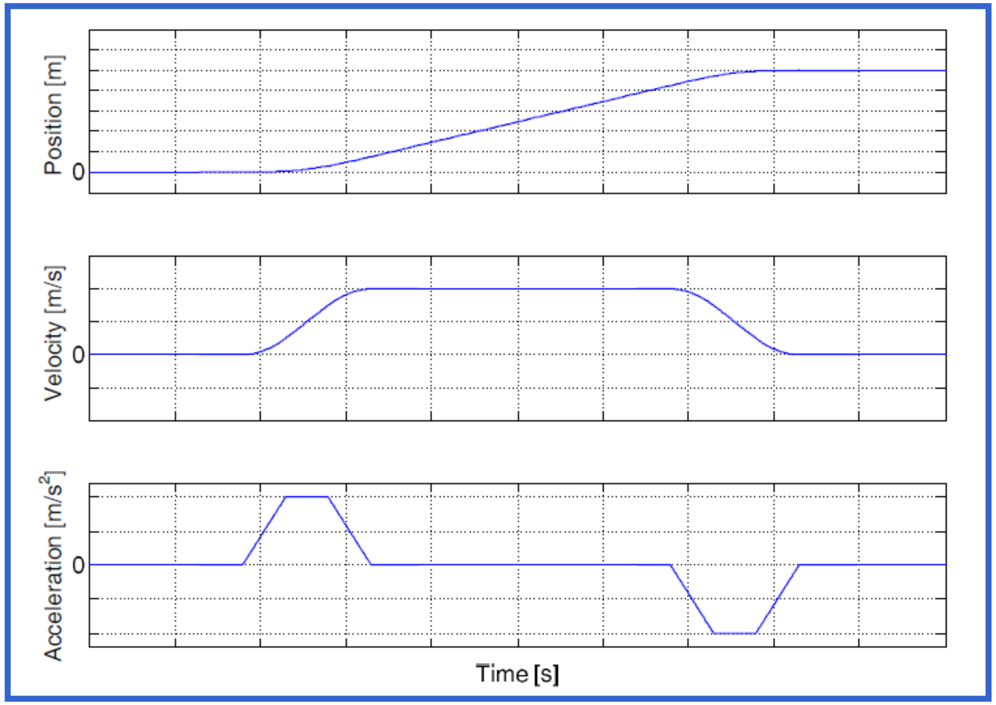
# Position Control

- **Control block diagram**



# Position Control

1 ➢ **S-curve profile command**



# Position Control

## 2 ➢ Total Sliding Mode Control

$$F = M\ddot{x} + B\dot{x} + F_L$$

⇩

$$\ddot{x}(t) = C_{1n}\dot{x}(t) + C_{2n}U(t) + W(t)$$

$$C_{1n} = -\frac{\bar{B}}{\bar{M}} \quad , C_{2n} = \frac{1}{\bar{M}}$$

$$U = F$$

$$W(t) = \text{lumped uncertainty}$$

# Position Control

② ➢ **Total Sliding Mode Control**

$$U = U_{BMC} + U_c$$

$U_{BMC}$ **: Baseline model control**

$U_c$ **: Curbing control**

# Position Control

② ➢ **Total Sliding Mode Control**

**:Baseline model control**

$$U_{BMC} = -C_{2n}^{-1}C_{1n}\dot{x} + C_{2n}^{-1}\left[\ddot{x} + k_p e + k_d \dot{e}\right]$$

**1st term to compensate nonlinear effects**

**2nd term to determine system performance**

# Position Control

## ② Total Sliding Mode Control

## :Curbing control

$$U_c(t) = -\rho(t) C_{2n}^{-1} \operatorname{sgn}(S(t))$$

**To eliminate the perturbation and uncertainty effects**

$$\left| W(t) \right| < \rho$$

**The selection of $\rho$ affects the chattering phenomena and system stability performance**

# Position Control

3 ➤ **Desired phase current command**

$$\begin{bmatrix} i_1^d \\ i_2^d \\ i_3^d \end{bmatrix} = \sqrt{\frac{|F^d|}{\gamma}} \begin{bmatrix} \cos x_1 & -\sin x_1 \\ \cos x_2 & -\sin x_2 \\ \cos x_3 & -\sin x_3 \end{bmatrix} \begin{bmatrix} 1 \\ \mathrm{sgn}(F^d) \end{bmatrix}$$

➤ **Constant parameters**

$$x_j = \frac{\pi}{p_t}x + (j-1)\frac{2\pi}{3}$$

$$\gamma = \frac{3\pi}{2p_t}(L_d - L_q)$$

# Position Control

3 ➢ **Current control**

$$u_j = k_i(i_j^d - i_j)$$

**- Desired phase voltage**

$k_i$ **= Current control parameter**

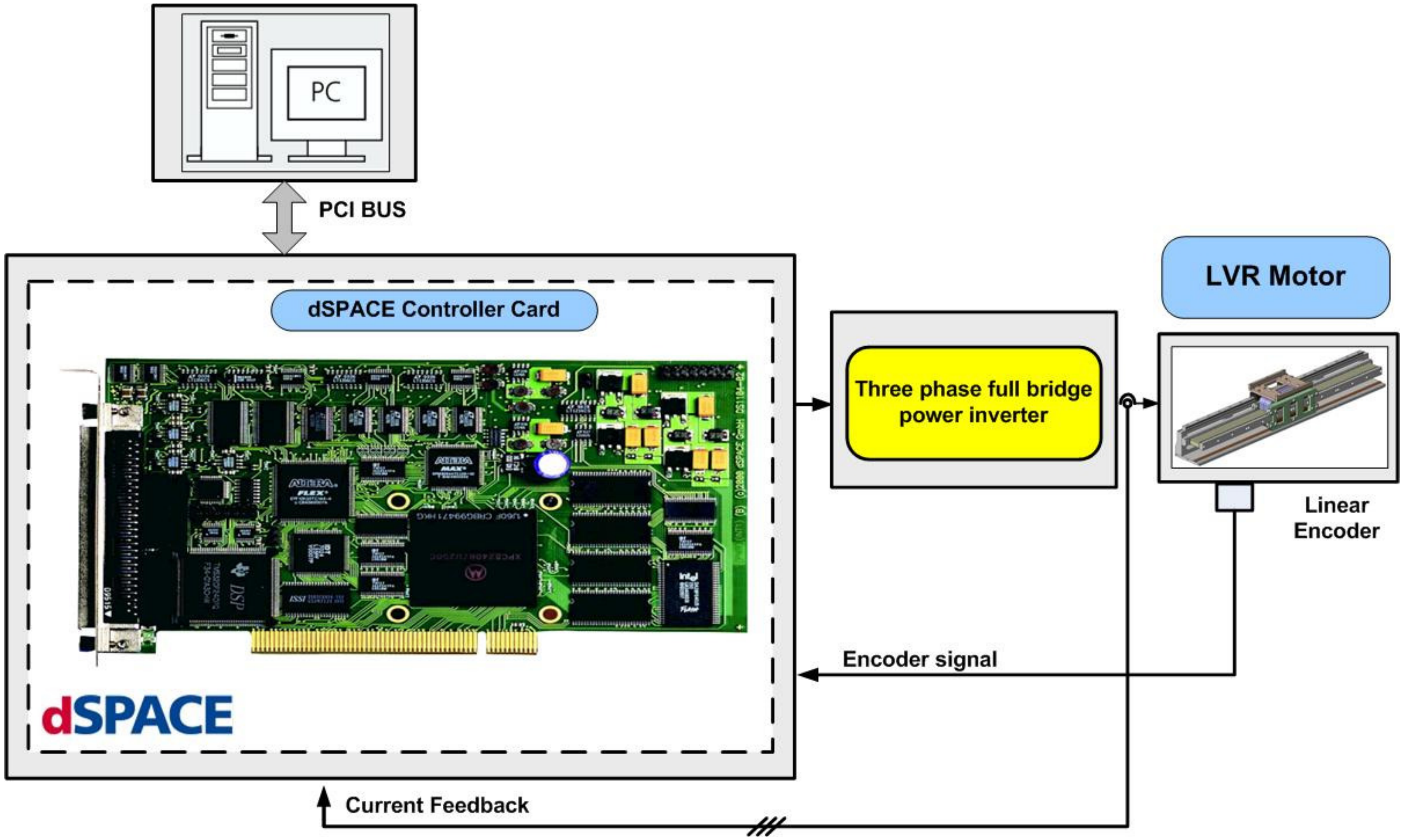
# Position Control

- **Experimental setup**

  - dSPACE controller board
  - Three phase power inverter
  - 14kg payload
  - Two desired trajectories for experimental test
    - Short-distance profile: 400 μm
    - Long-distance profile: 10 cm
  - Two controllers for experimental test
    - Input-output linearization control [8]
    - Total sliding mode control

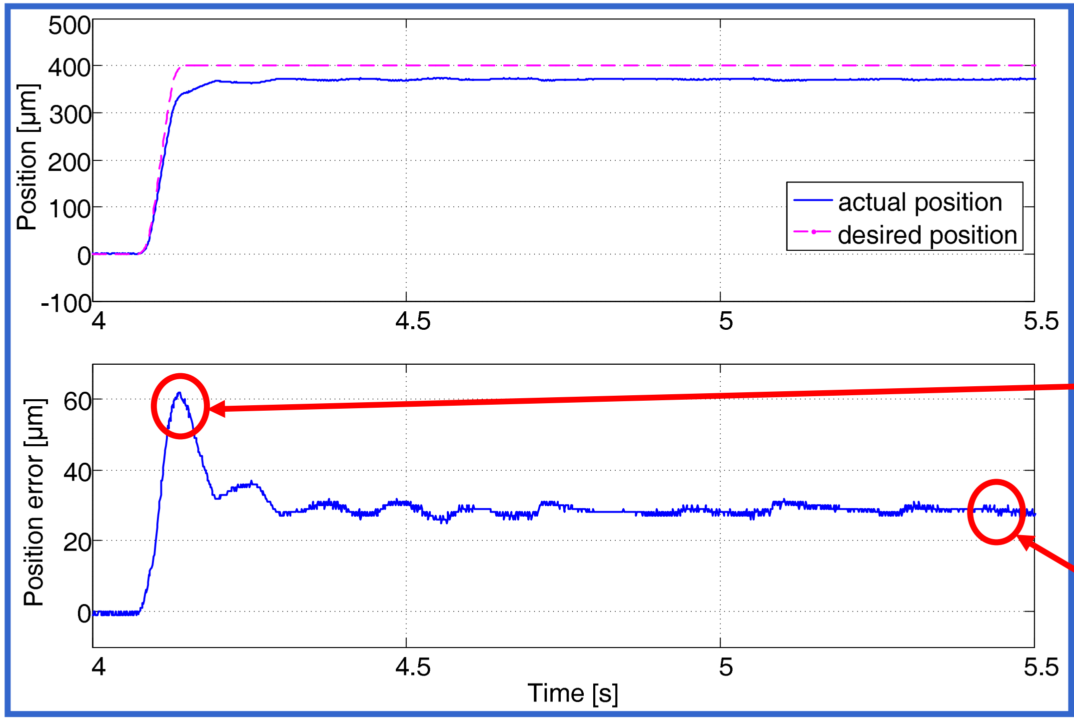
# Position Control

➢ **Experimental setup**



# Experimental Results

**Position and position error responses for short-distance profile: 400 µm**



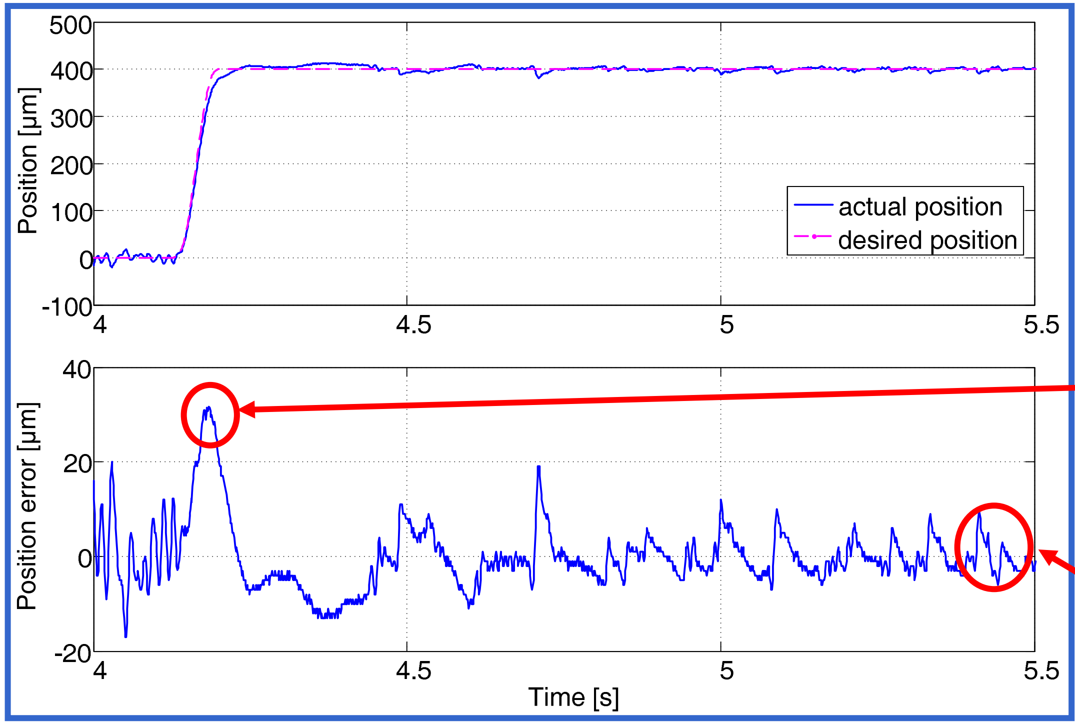

**Previous [8] Control**

**Max dynamic error ≈ 61.9 µm**

**Steady state error ≈ 27.5 µm**

# Experimental Results

**Position and position error responses for short-distance profile: 400 µm**



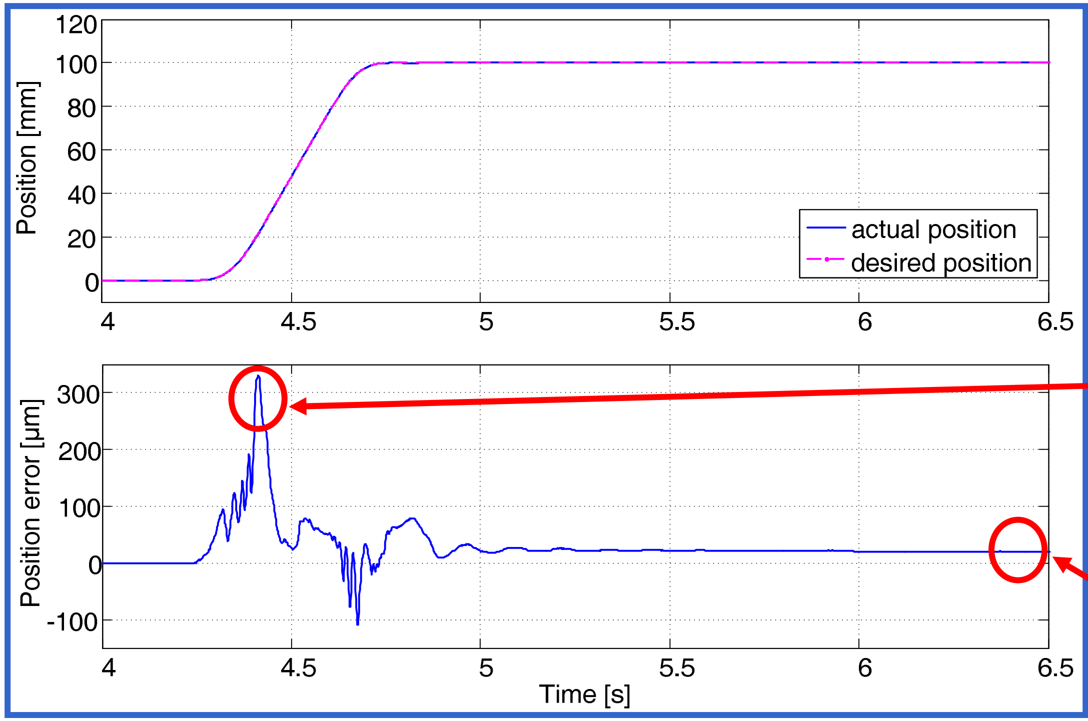

**Total Sliding Mode Control**

**Max dynamic error ≈ 31.7 µm**

**Steady state error ≈ 10 µm**

# Experimental Results

**Position and position error responses for long-distance profile: 10 cm**



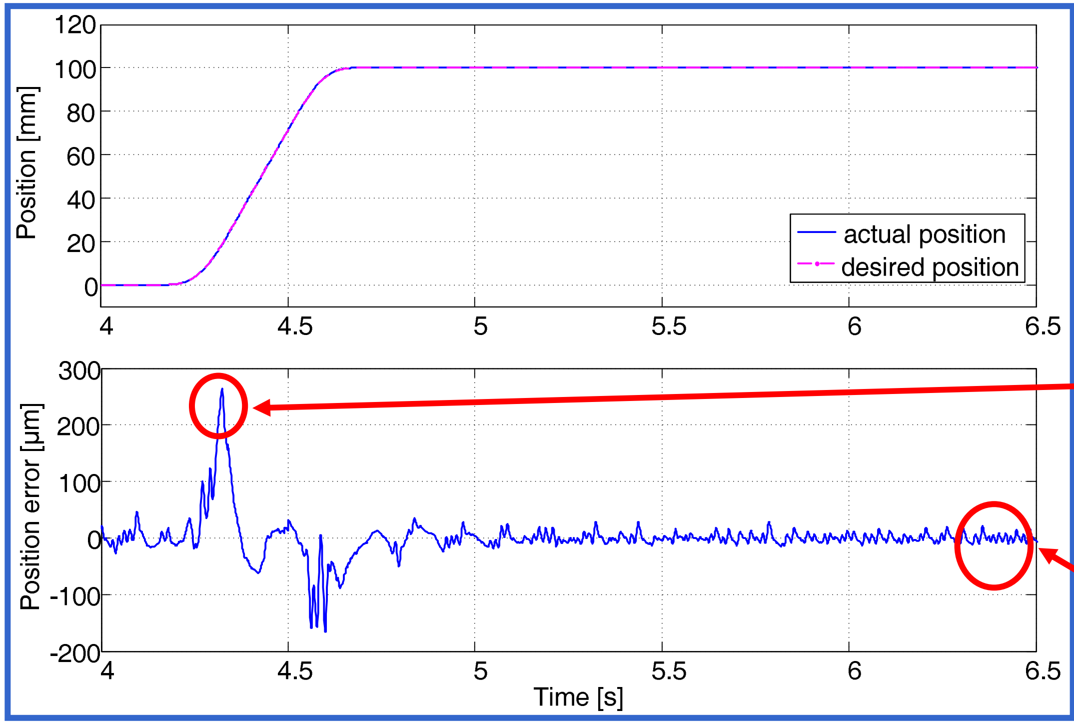

**Previous [8] Control**

**Max dynamic error ≈ 331.4 μm**

**Steady state error ≈ 22 μm**

# Experimental Results

**Position and position error responses for long-distance profile: 10 cm**




**Total Sliding Mode Control**

**Max dynamic error ≈ 264 µm**

**Steady state error ≈ 15 µm**

# Conclusions/Future work

- **Advantages**
  - Simple and computationally efficient for implementation
  - System robustness to parameter variations
- **Disadvantages**
  - Chattering phenomena problem
  - Future work to reduce chattering phenomena to achieve higher accuracy for high-precision application

# Thank You