EE5111/EE5061 Selected Topics in Industrial Control & Instrumentation

Precision Motion Systems

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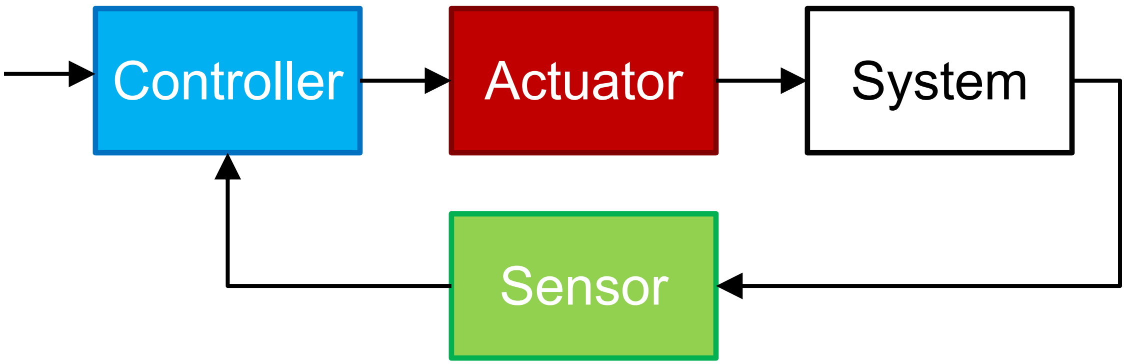
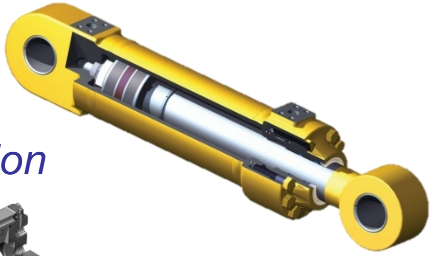
Recap

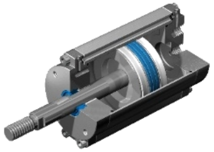
- **Feedback Control**
  - A Feedback Control System can be applied to
    - Process control
    - Motion control
      - *Speed control*
      - *Position control*
    - Force control
      - *Direct force control*
      - *Impedance control*
- **How?**
  - Controller
  - **Actuator**
  - Sensor

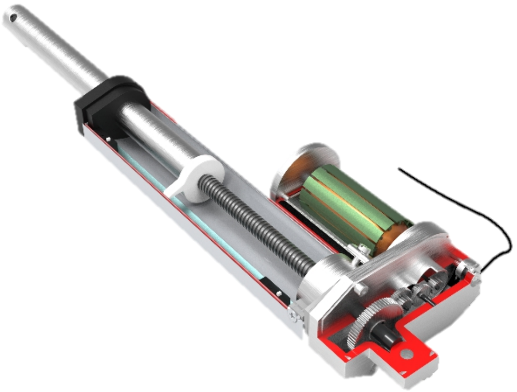


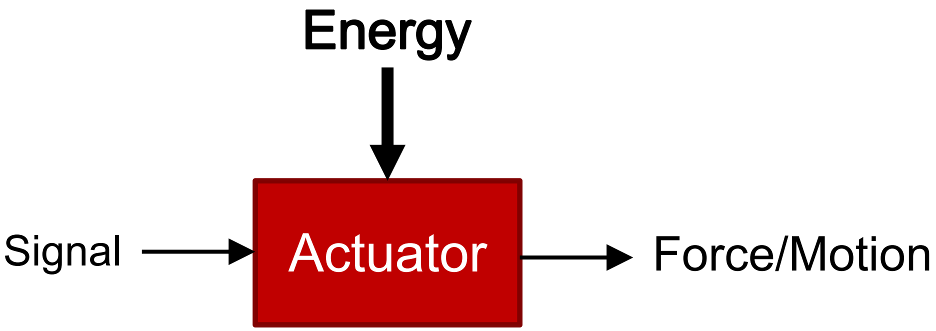
Overview

- **Actuator**
  - An **actuator** is a component of a machine that is responsible for moving and controlling a mechanism or system
    - Hydraulic
      - *uses hydraulic power to facilitate mechanical operation*
    - Pneumatic
      - *commonly powered by compressed air*
    - Electric
      - *mainly refers to electric motor, which converts electrical energy into mechanical energy*









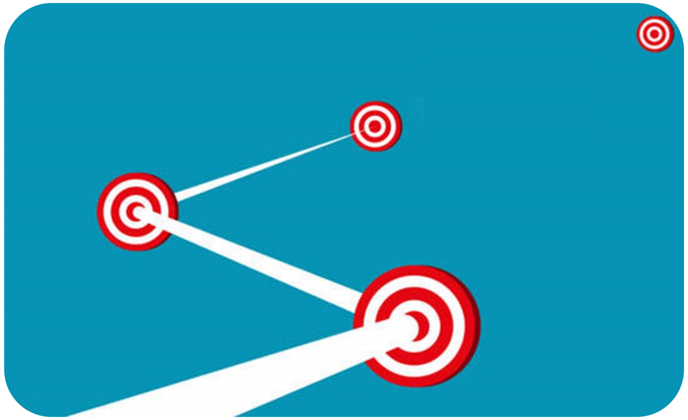
Topics to Be Covered

- **Precision Actuators (linear motion)**
  - Common methods
  - Examples
- **Friction Compensation**
  - Basic concepts
  - Main methods
  - Examples
- ***Industrial Control Systems**

Precision Actuators

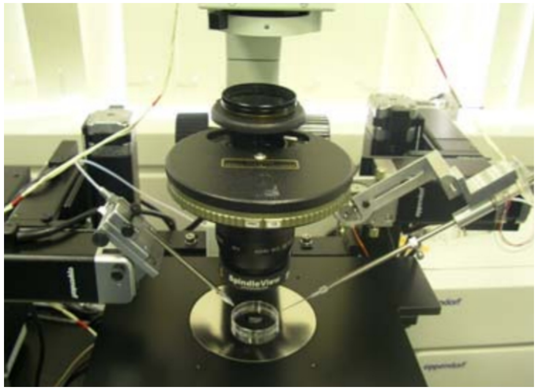
Precision Actuators

- What?
  - To achieve good positioning or tracking performance with high speed and high accuracy
- Motion Types
  - Rotary
  - Linear
- How?
  - Direct-drive technology
  - Reducing friction
    - Friction-less bearings
    - Friction compensation



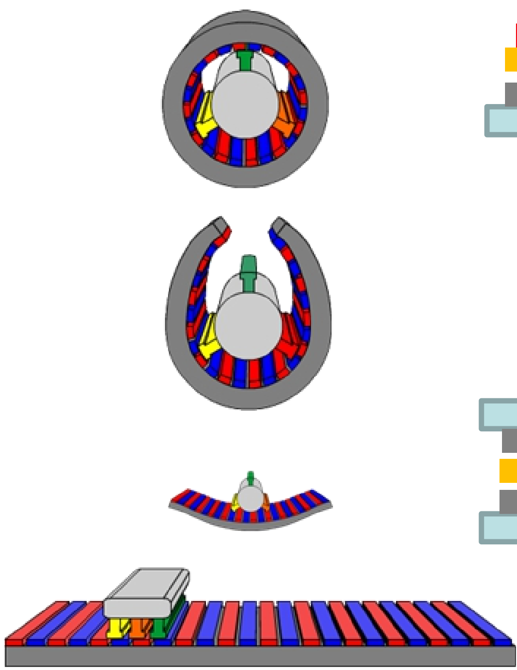
Precision Actuators - Direct-drive technology

- **Direct-drive technology**
  - directly drives a mechanism without any intermediate drivetrain (such as a gearbox or timing belt, etc.)
- **Main types**
  - Permanent Magnetic Linear Motor (PMLM)
  - Voice Coil Actuator (VCA)
  - Piezoelectric Actuator/Motor (PA/PM)

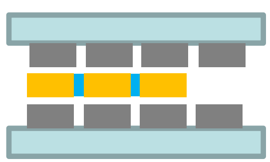


Precision Actuators - Direct-drive Technology

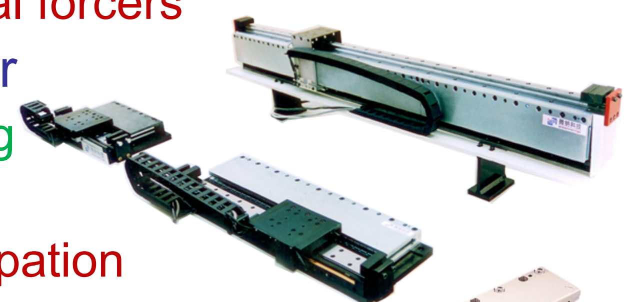
- Permanent Magnet Linear Motor (PMLM)

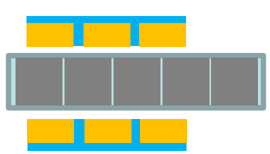


- Iron core linear motor
  - High force
  - Cogging
  - Eddy currents
  - Attractive and lateral forcers



- U-shaped linear motor
  - Ironless, no cogging
  - Higher cost
  - Reduced heat dissipation
  - Lower stiffness

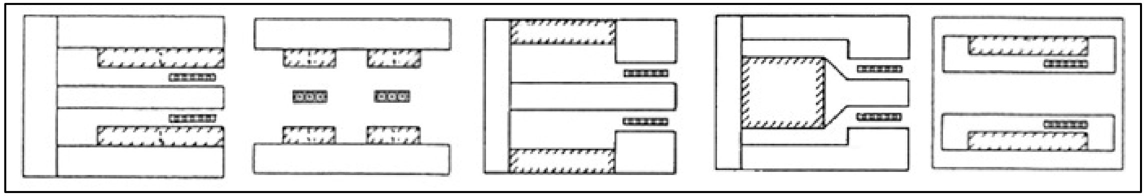


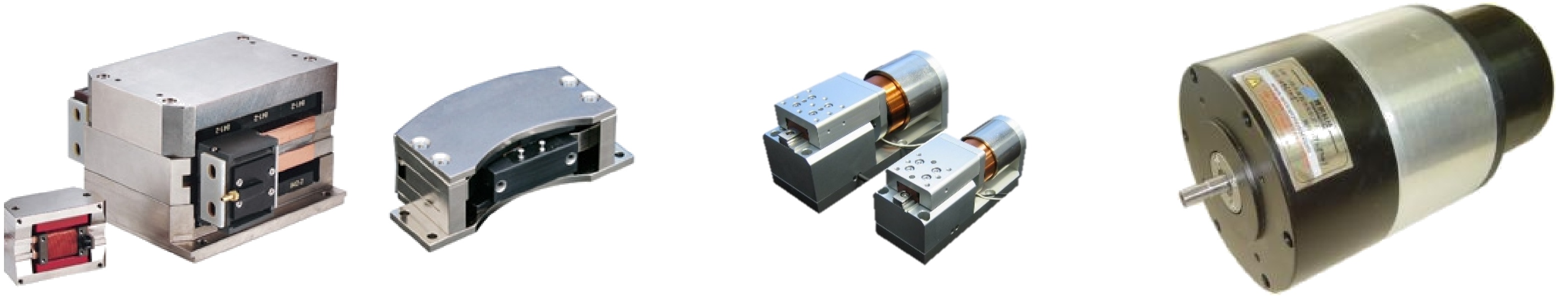


- Tubular linear motor
  - Smoothness
  - Good stiffness
  - Efficient cooling
  - More height, limited travel range

Precision Actuators - Direct-drive Technology

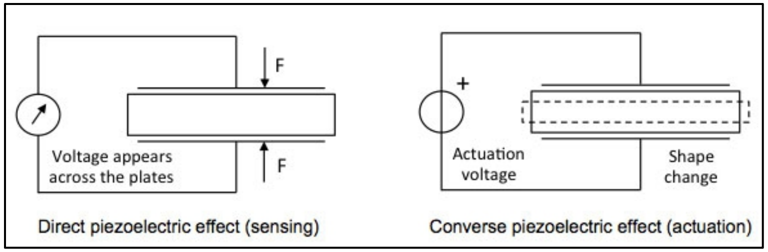
- Voice Coil Actuator (VCA)
  - Also known as <u>Voice Coil Motor (VCM)</u>
  - Usually classified as a brushless DC actuator
  - Works on the principle of the Lorentz force
  - Advantages
    - Miniaturization
    - Rapid response
    - High accuracy
    - High stiffness (i.e., high resistance to deformation)
    - Easy to operate





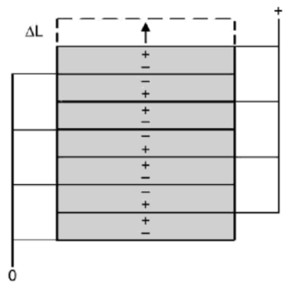
Precision Actuators - Direct-drive Technology

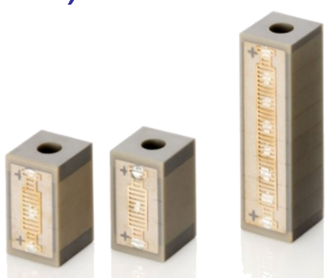
- **Piezoelectric Actuator or Motor (PA/PM)**
  - Converts electrical energy into a mechanical displacement or stress based on a piezoelectric effect
  - Offers the advantages of **fine accuracy, high speed & resolution**
  - Widely used in precision engineering and high-accuracy applications
    - Nano-fabrication: ultra-precision machining tools
    - Dynamic imaging of molecules by using scanning probe microscopes (SPMs), atomic force microscopes (AFMs);
    - Advanced spacecraft with optical sensitive instruments
    - Medical devices and surgical robots
    - …
  - Main types
    - **Direct Piezoelectric Actuator**
    - **Amplified Piezoelectric Actuator**
    - **Ultrasonic Motor**



Precision Actuators - Direct-drive Technology

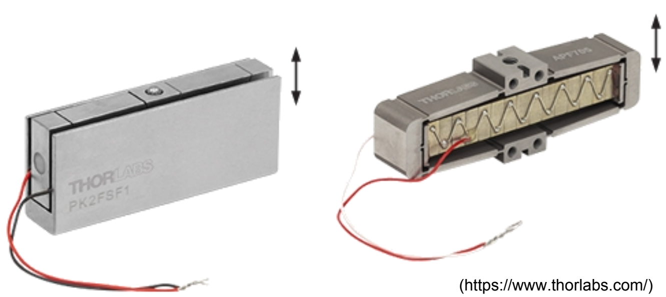
- **Direct Piezoelectric Actuator**
  - Single design (high force with small size)
  - Stack design





(https://www.physikinstrumente.com/)

- **Amplified Piezoelectric Actuator**
  - amplify the piezo stroke by
    - lever arm or
    - flextensional mechanism



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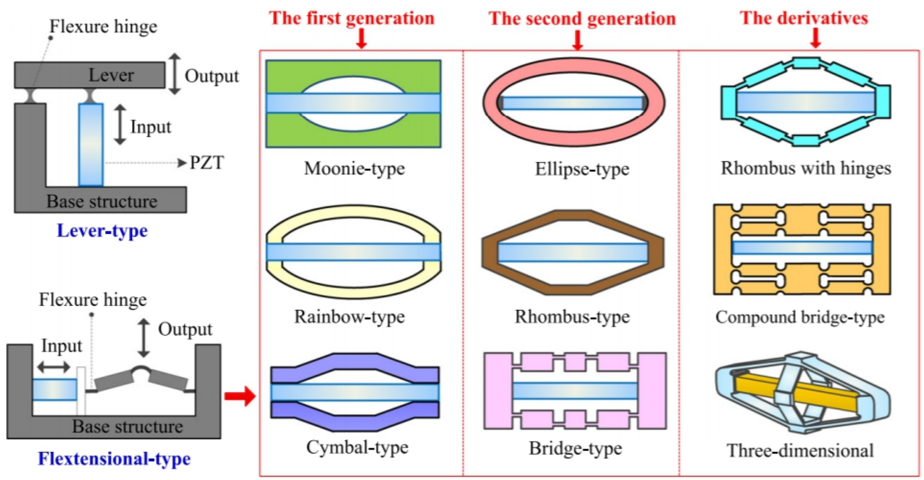
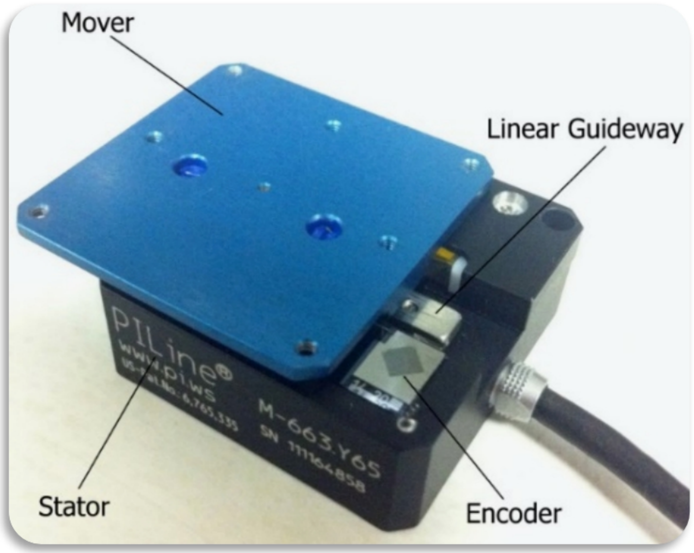
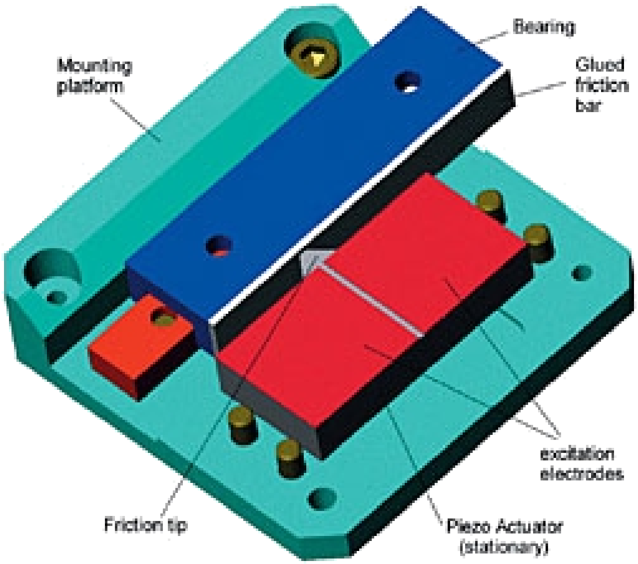


(M. Ling; J. Cao; M. Zeng; J. Lin; D. J. Inman, "Enhanced mathematical modeling of the displacement amplification ratio for piezoelectric compliant mechanisms," *Smart Materials and Structures,* vol. 25, no. 7, pp. 075022, Jun. 2016)

Precision Actuators - Direct-drive Technology

- **Ultrasonic Motor (USM): one type of PA/PMs**
  - Offer larger traveling distance than other type of PA/PMs
    - Example: M-663 (*Physik Instrumente (PI) GmbH & Co. KG.*)
      - *Min. motion: 0.3* µm *(precise)*
      - *Max. velocity: 400* mm/s *(fast)*
      - *Travel range: 19 mm (theoretically* unlimited*)*





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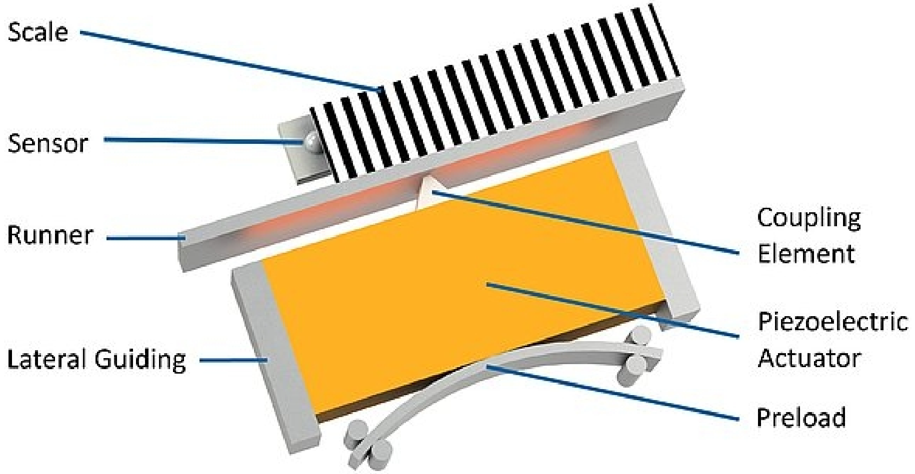
Precision Actuators - Direct-drive Technology

- **Ultrasonic Motor (USM)**
  - Working Principle
    - The USM works based on the principle of asymmetric **resonant excitation** of the piezoceramic plate in a two-dimensional extensional mode
    - The movement of the USM is generated by the **friction** between the piezoceramic plate fixed in the stator and the friction bar mounted on the mover



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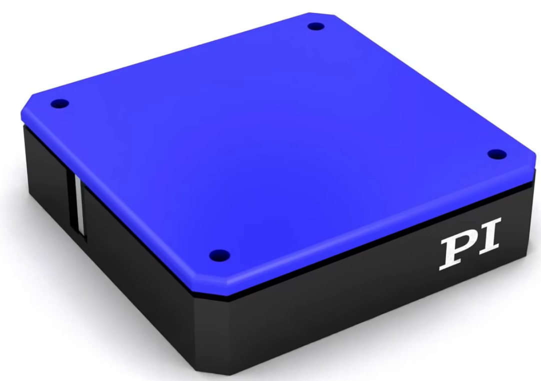

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Precision Actuators - Direct-drive Technology

- Conventional driving system
  - Low precision (backlash and elasticity)
  - Slow dynamic response (velocity is limited)
  - Limited output torque and efficiency
  - Complicated in mechanical structure, bulky and heavy
  - Lack of flexibility

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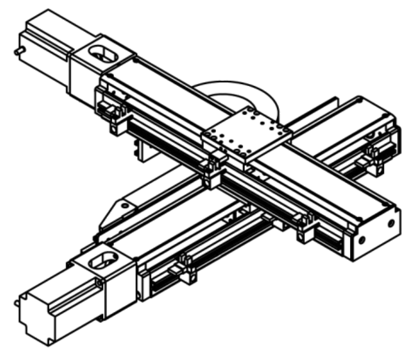
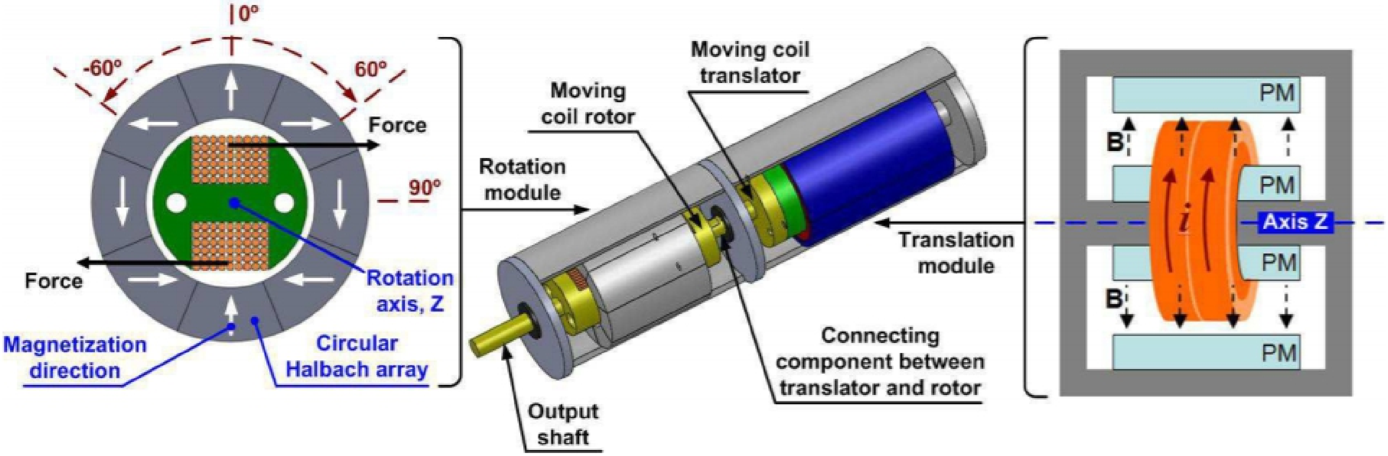


- Direct-drive system
  - High precision, more efficient motion
  - Faster positioning time
  - High torque output and low moment of inertia

Precision Actuators - Direct-drive Technology

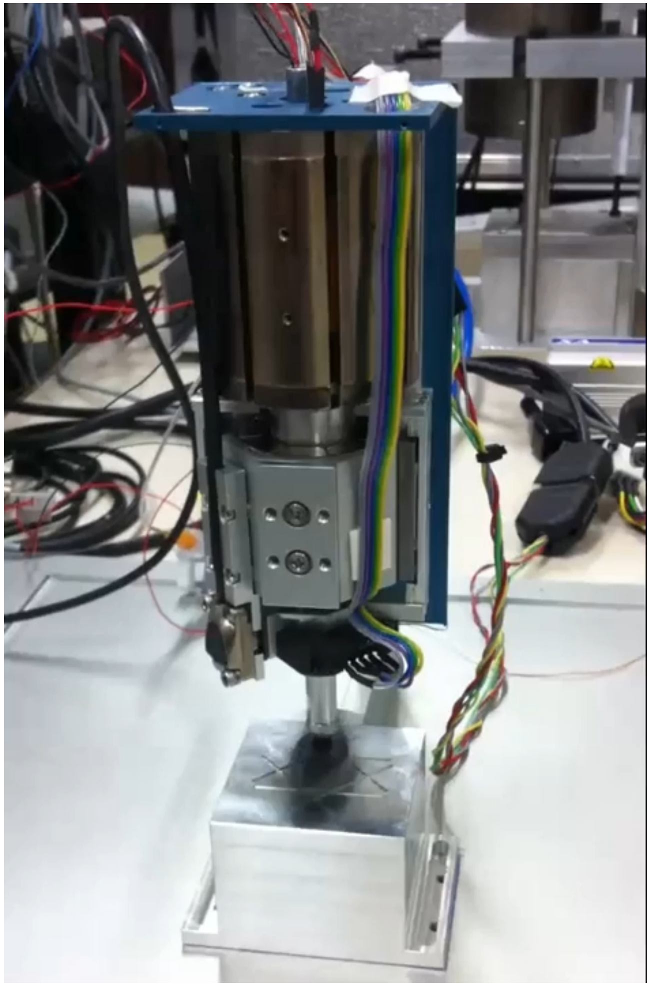
- 2-DOF Linear-Rotary Actuator
  - Linear module
    - dual-magnet configuration (high efficient)
  - Rotary module
    - single-phase limited-angle torque (LAT) motor with cylindrical Halbach
      - *achieve high torque within a compact-size module*



(S.-L. Chen; T. J. Teo and G. Yang, "Control of an 2-DOF electromagnetic actuator for high precision and high-throughput pick-and-place tasks," *2013 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, pp. 146-151, Jul. 2013)

Precision Actuators - Direct-drive Technology

- 2-DOF Actuator - demo video
  - Application: IC pick-and-place



Precision Actuators - Reducing Friction

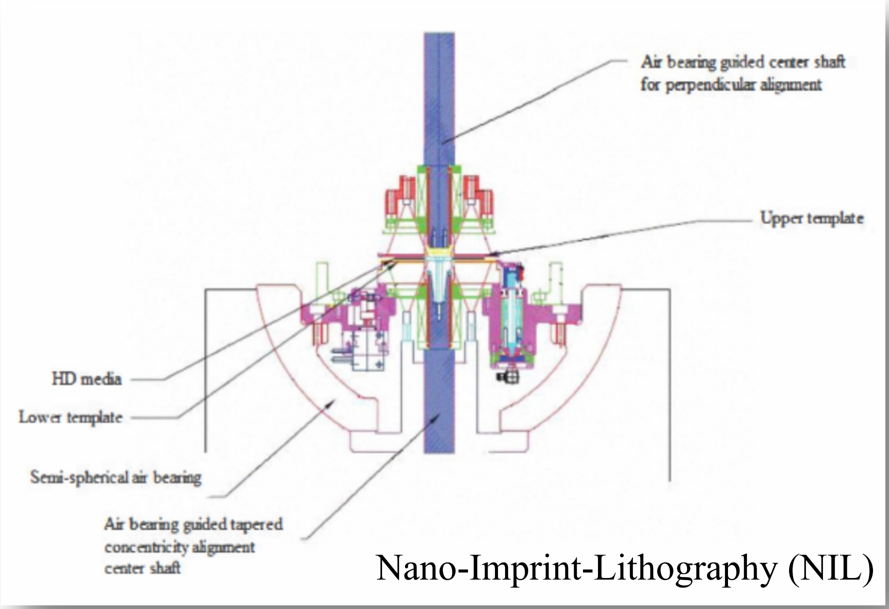
- **Bearing**
  - A **bearing** is a machine element that constrains relative movement to the desired motion and reduces friction between moving parts
  - The most common type is **rolling-element bearing** (ball bearing, roller bearing)
- **Friction-less bearings**
  - Air bearing (a type of Fluid bearing)
    - The load is supported by a gas
  - Magnetic bearing
    - The load is supported by a magnetic field (magnetic levitation)
  - Flexure bearing
    - The motion is supported by a load element which bends

Precision Actuators - Examples

Spherical Air Bearing Positioning Stage

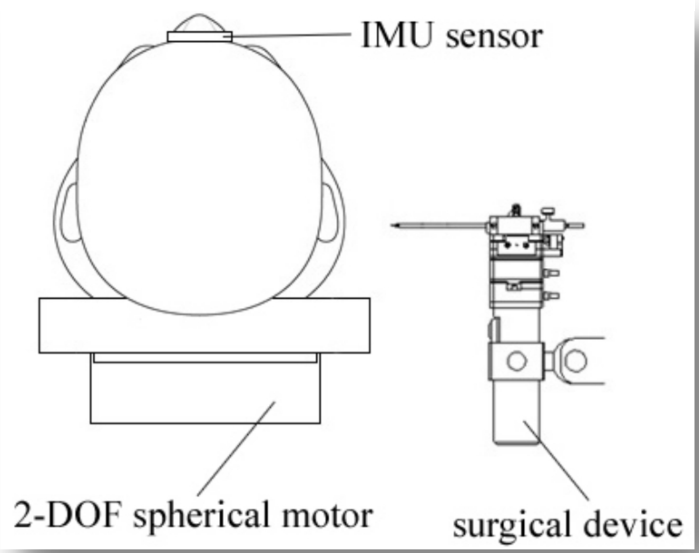
Spherical Air Bearing Positioning Stage

- **Introduction**
  - As the level of automation rises in the modern world, more and more equipment are required to achieve <u>**multi-DOF**</u> motion
    - **Spherical motion systems** can be applied to various applications, such as robot joints, manipulators, steering systems, vehicle wheels, machines which require orientation control, medical applications



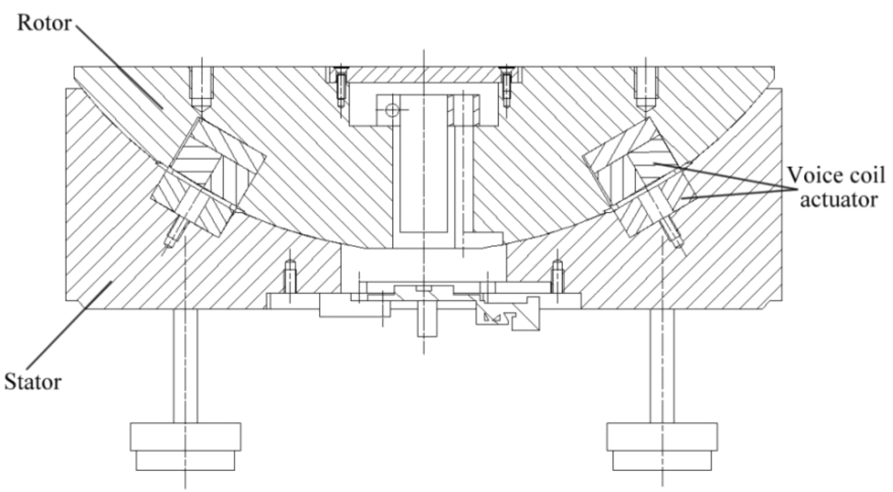
Nano-Imprint-Lithography (NIL)

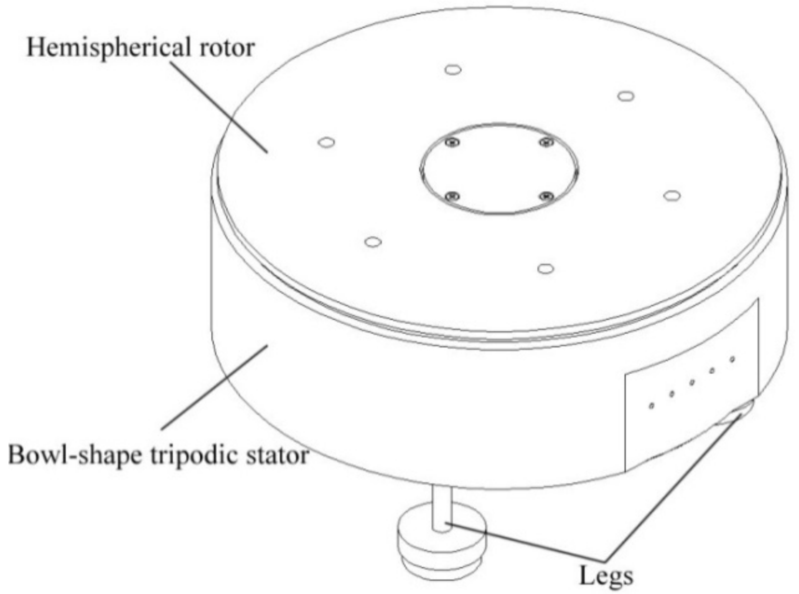
Surgical Device



Spherical Air Bearing Positioning Stage

- **A solution for 2-DOF angular motions**
  - Spherical Air Bearing Positioning Stage (SABS)
    - aiming at providing highly precise rotational motions in 2-DOF
    - Mechanical Structure
      - *Hemispherical solid rotor (112* mm *in diameter)*
      - *Bowl-shaped stator*



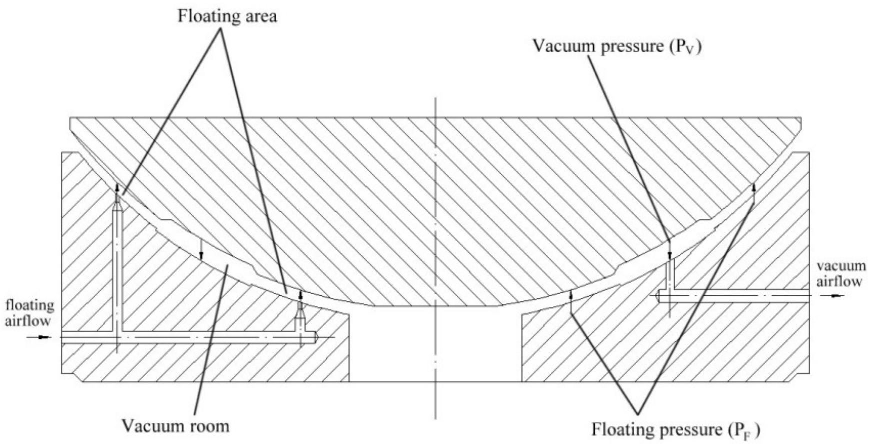


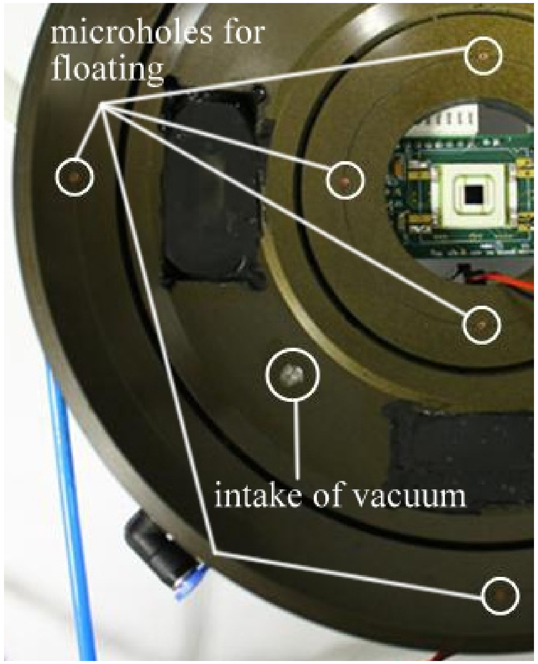
Spherical Air Bearing Positioning Stage

- **Pneumatic System**
  - When **a thin air film** is introduced between the two components, the rotor floats on the air film
  - **Hydrostatic type:** air film is provided from external pressure supply
    - **Floating Forces** generated by the air pressure

$$F_p = PA$$

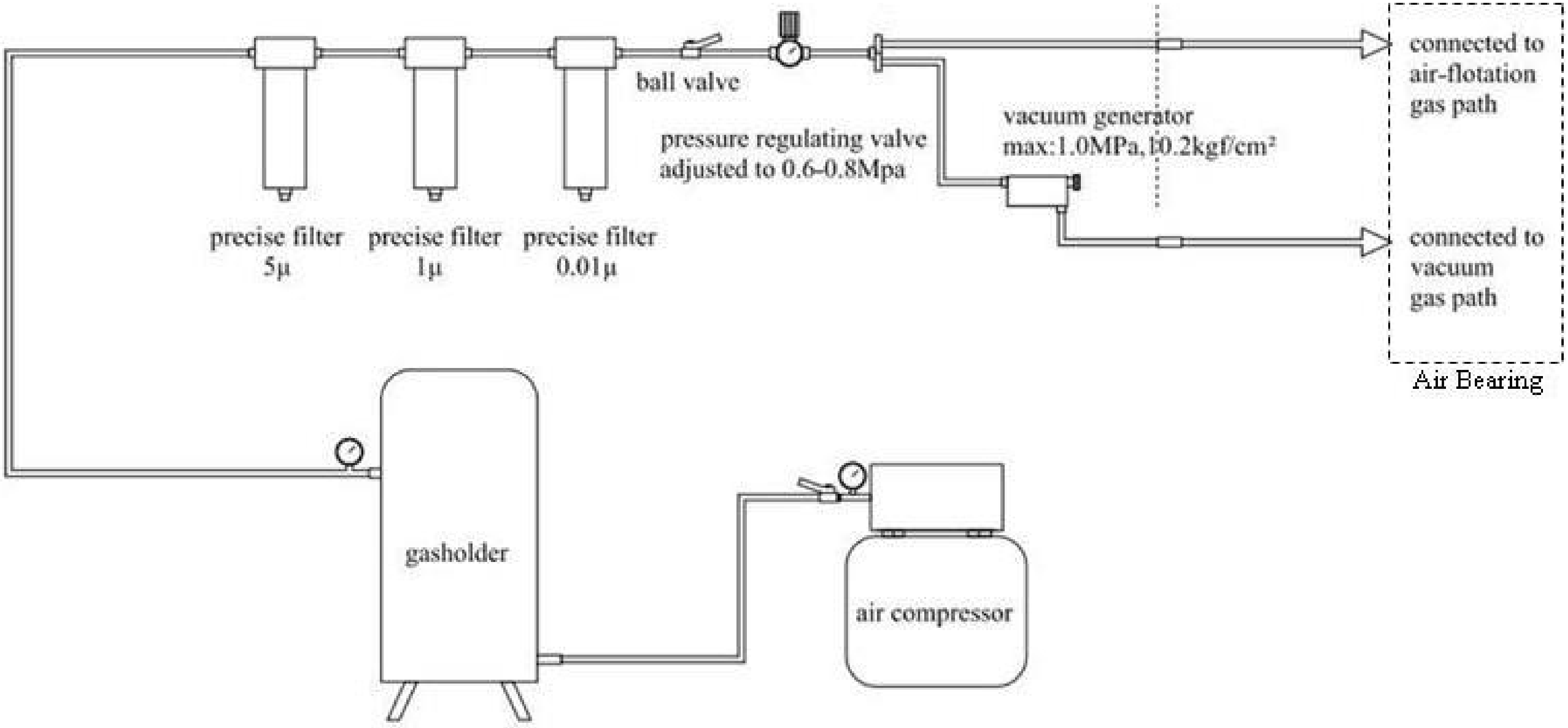
  - **Vacuum Preload**
    - Help it to improve system stiffness





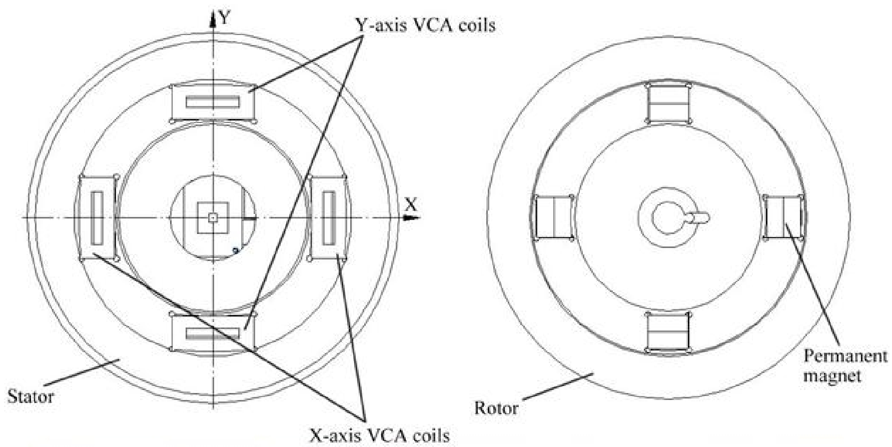
Spherical Air Bearing Positioning Stage

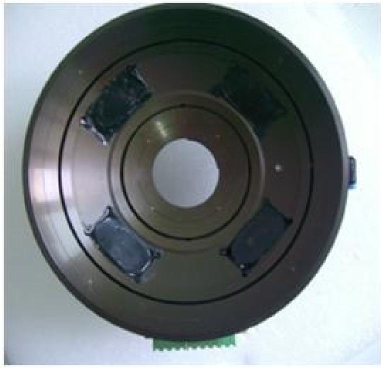
- Pneumatic System

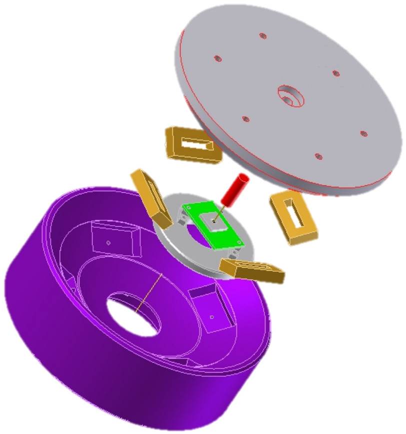


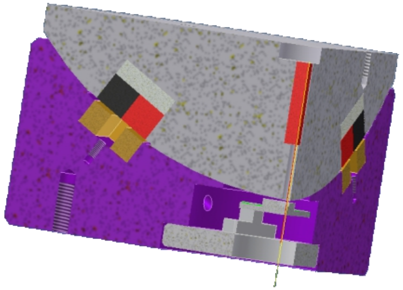
Spherical Air Bearing Positioning Stage

- **Actuator Design**
  - Voice Coil Actuators (VCAs)
    - Four, symmetric mounting
    - Coils mounted in the stator
    - Permanent magnets (with magnetic yokes) in the rotor
      - *made of NdFeB (Neodymium Iron Boron)*
      - *two magnets are placed side by side on one soft iron yoke*









Spherical Air Bearing Positioning Stage

- **Actuator Design**
- **Working Principle of VCA**
  - Lorentz force law

$$F_a = k\overrightarrow{B_y} \times \overrightarrow{L} N i$$

Due to the symmetrical structure

$$F_b + F_b' + F_c + F_c' = 0$$

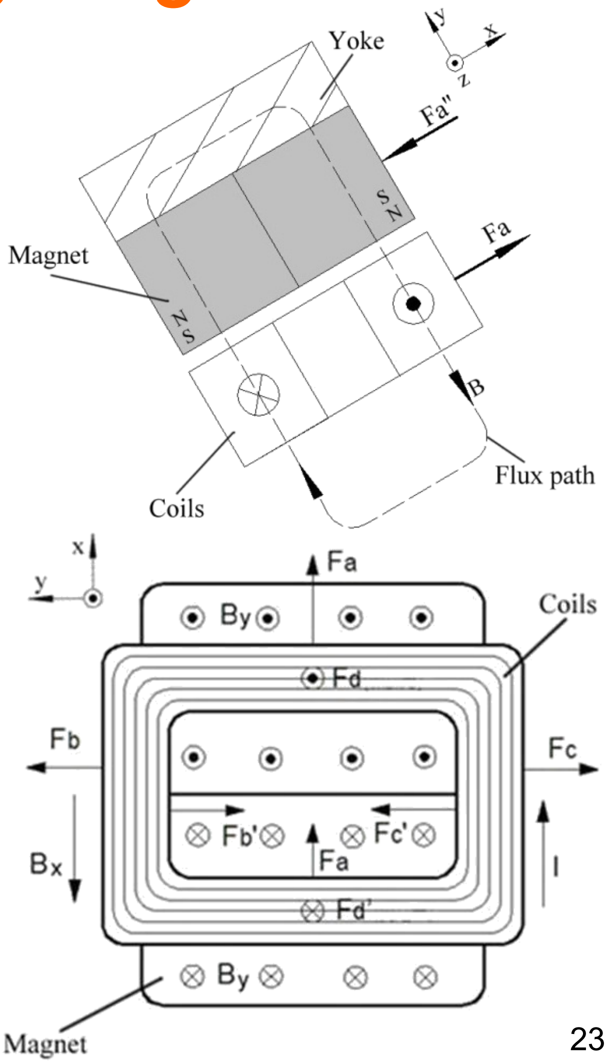
Force and torque in z-axis

$$F_d = F_d'$$

$M_d \approx F_d d$ is too small, ignored

- **Generated force:** $F_a = kB_y lNi$

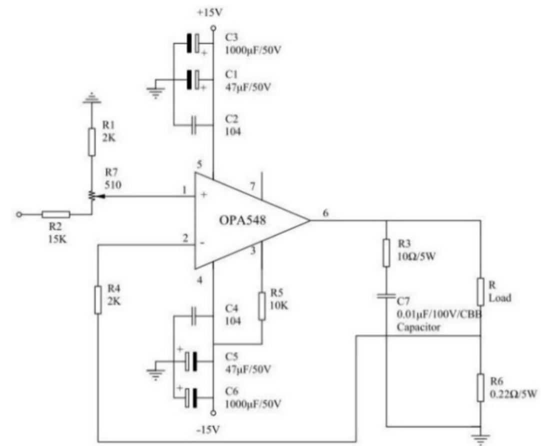
in the tangential direction of rotor

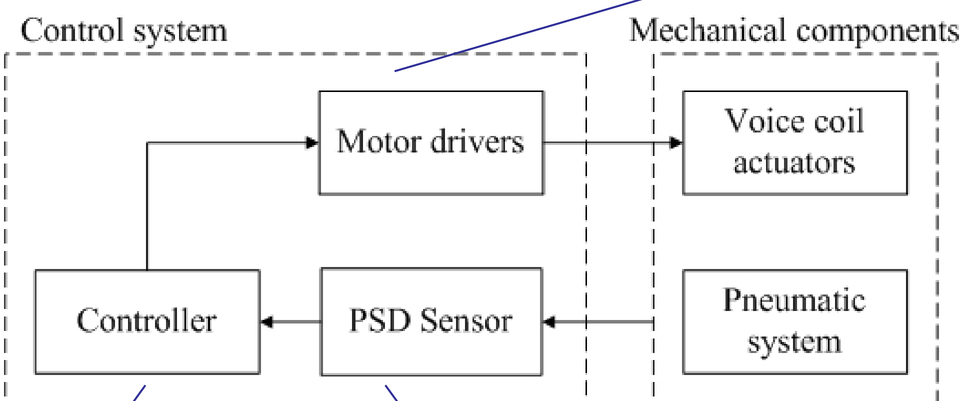


Spherical Air Bearing Positioning Stage

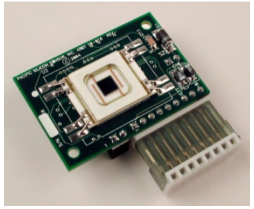
- **Electrical System**

High-voltage, high-current operational amplifier (OPA 548)

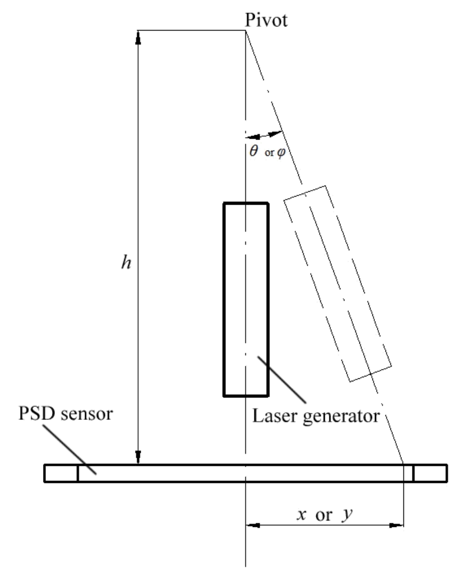




dSPACE control card



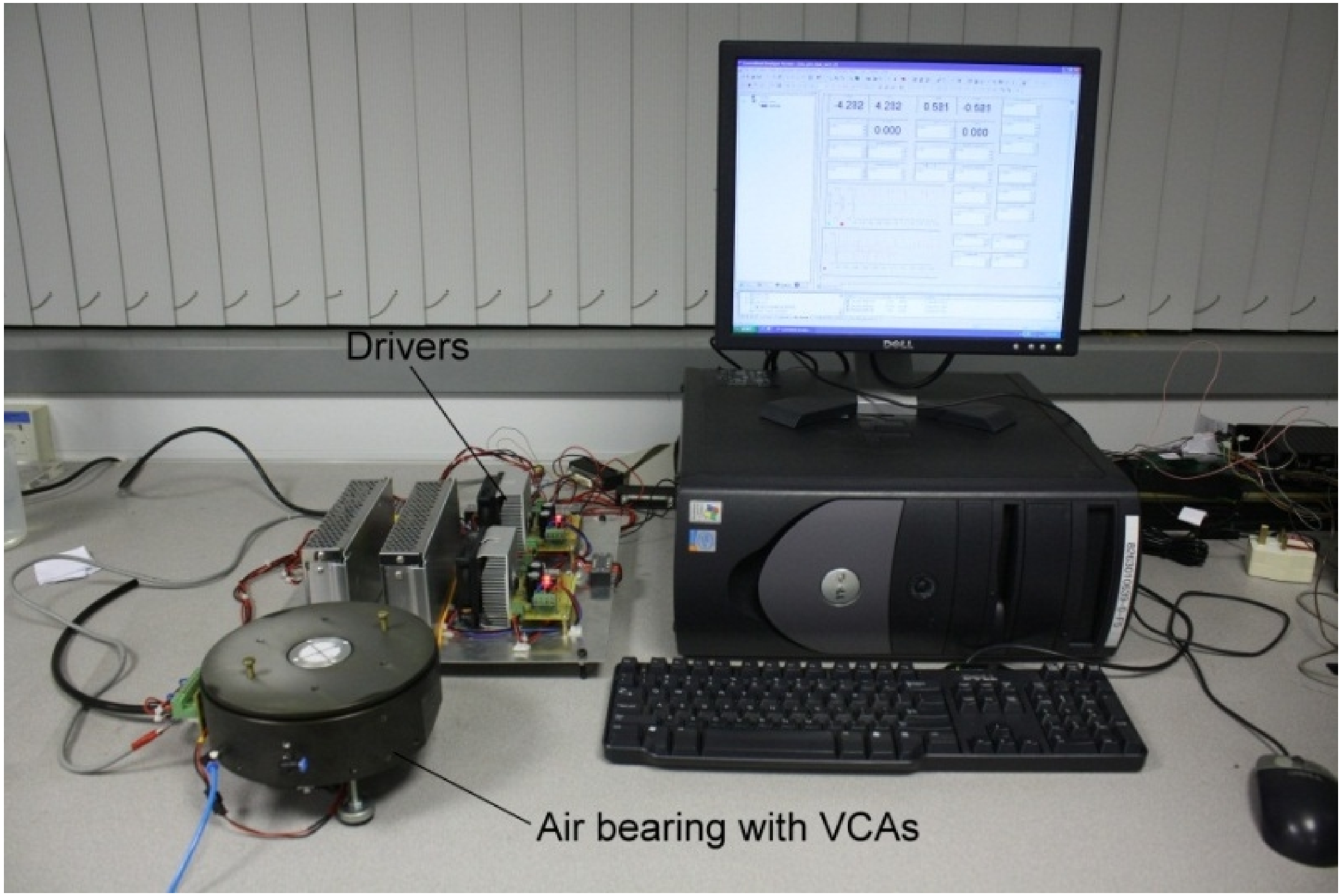
$$\begin{cases} \theta = \arctan(\frac{y_s}{h}) \\ \varphi = \arctan(\frac{x_s}{h}) \end{cases} \Rightarrow \begin{cases} \theta \approx \frac{y_s}{h} \\ \varphi \approx \frac{x_s}{h} \end{cases}$$



Dual axis position sensing diode (PSD)

Spherical Air Bearing Positioning Stage

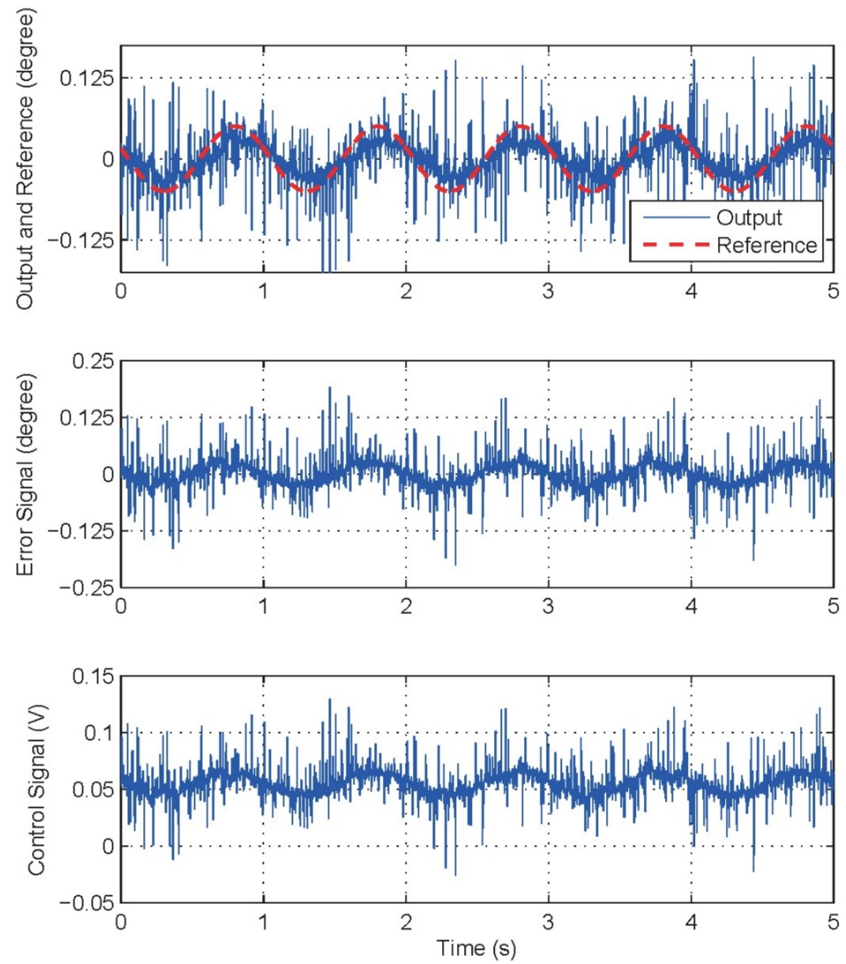
- System Setup



Spherical Air Bearing Positioning Stage

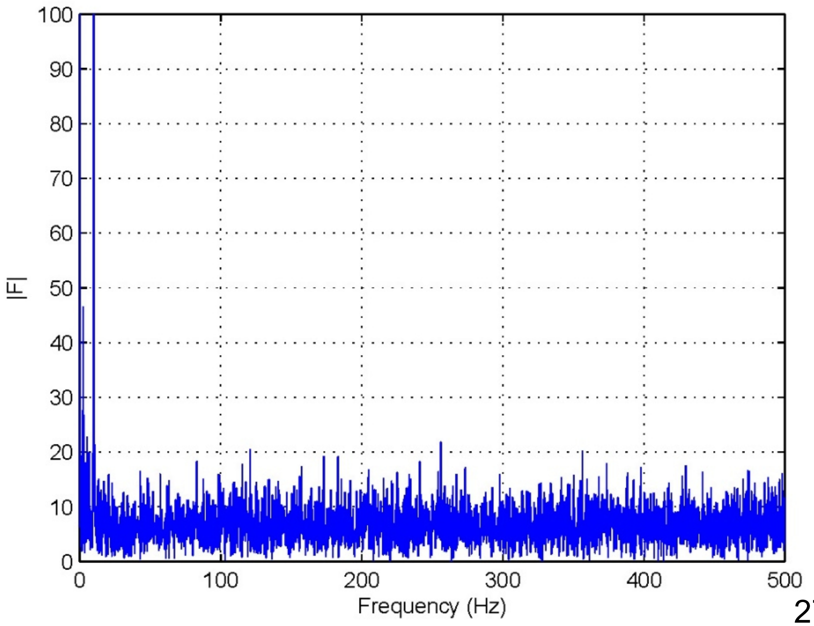
- **Traditional PID Controller**
  - Max. absolute error: **0.25deg**

$$i = K_P(y_d - y) + K_I\int_0^t (y_d - y)d\tau + K_D\frac{d(y_d - y)}{dt}$$



Spherical Air Bearing Positioning Stage

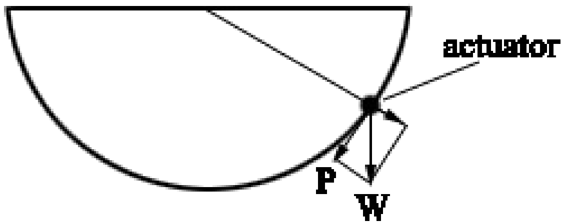
- **Sensor Measurement Noise**
  - Investigate on the measurement noise
    - Open loop
    - Input signal: 10Hz sine wave
    - Fast Fourier Transform (FFT)
  - Exhibits the characteristics of white noise



Spherical Air Bearing Positioning Stage

- **Observer-based Controller**
  - An Observer-type Filter is used for handling such noise
    - Modelling

$$\begin{cases} m_1\ddot{x}_1 = F_1 - P_1 \\ m_2\ddot{x}_2 = F_2 - P_2 \end{cases} \qquad F = kB_yLNi$$



    - State-space model (single axis)

$$\begin{cases} \dot{X} &= AX + B(bi - a) + w \\ y &= CX + v \end{cases}$$

$$A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, B = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, C = [1\ 0]$$

$$a = \frac{P}{m}, b = \frac{kB_yLN}{m}$$

    - Observer-type filter (needs the system model)

$$\begin{cases} \dot{\hat{X}} &= A\hat{X} + B(bi - a) + K(y - \hat{y}) \\ \hat{y} &= C\hat{X} \end{cases}$$

Spherical Air Bearing Positioning Stage

- **Parameter Estimation (Adaptive Control Technique)**
  - Define a filtered error $S = \lambda e + \dot{e} \qquad e = x_d - x$

$$\dot{S} = \lambda \dot{e} + \ddot{x}_d + \frac{P}{m} - \frac{kB_y LNi}{m} = \lambda \dot{e} + \ddot{x}_d + a - bi$$

  - Apply the adaptive control law $i = \dfrac{K_v S + \lambda \dot{e} + \ddot{x}_d + \hat{a}}{\hat{b}} \qquad \dot{\hat{a}} = \gamma_1 S \qquad \dot{\hat{b}} = -\gamma_2 i S$

$\Rightarrow \quad \dot{S} = \tilde{a} - \tilde{b} i - K_v S$

  - Define $V = S^2 + \dfrac{1}{\gamma_1}\tilde{a}^2 + \dfrac{1}{\gamma_2}\tilde{b}^2$ we have $\dot{V} = -2K_v S^2 < 0$

S, $\hat{a}$ and $\hat{b}$ are bound

$\int_0^t K_v S^2 d\tau = [V(0) - V(t)]/2 \le V(0)/2$ and $\dot{S}$ is also bound $\Rightarrow \lim_{t \to \infty} \|S\|_2 = 0$

tracking error converges to zero

  - The parameters $\hat{a}$ and $\widehat{b}$ converge to 0.0001 and 0.0755

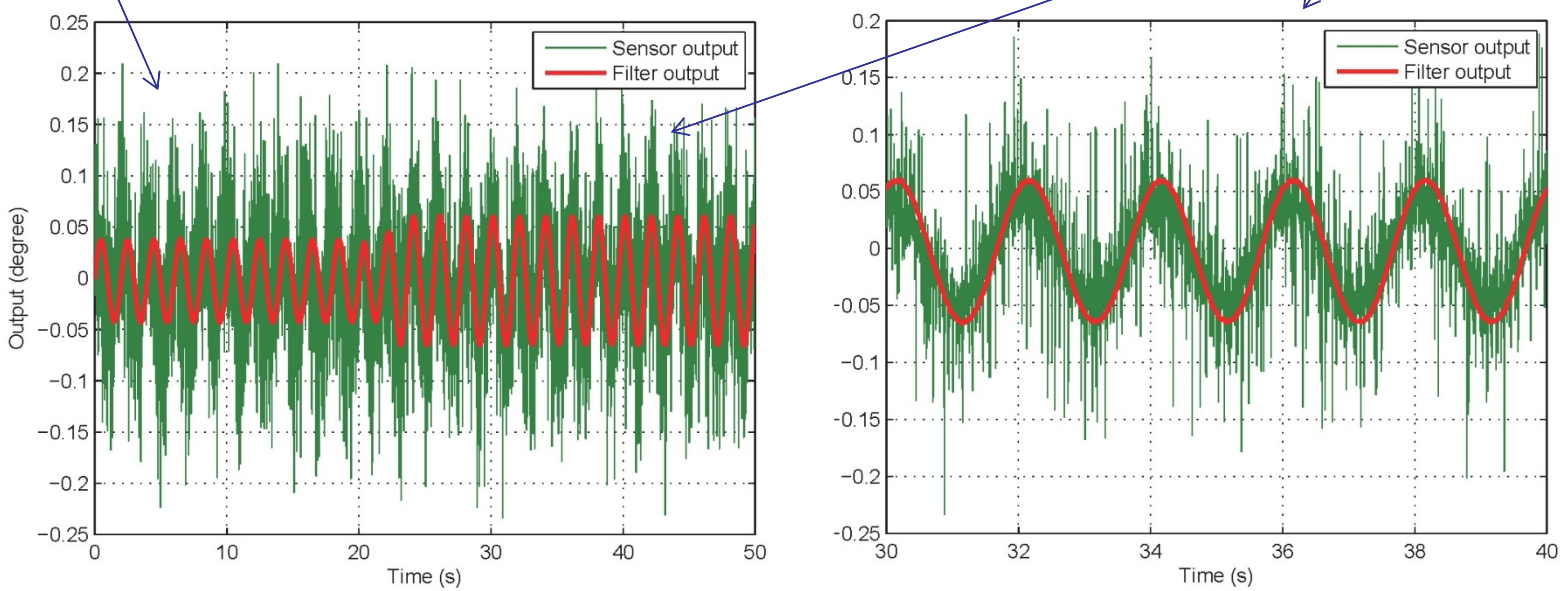
Spherical Air Bearing Positioning Stage

- **Noise Filter Design**
  - Based on the model, the filter is designed
  - Trail-and-Error

$$K = \begin{bmatrix} 5 \\ 25 \end{bmatrix}$$

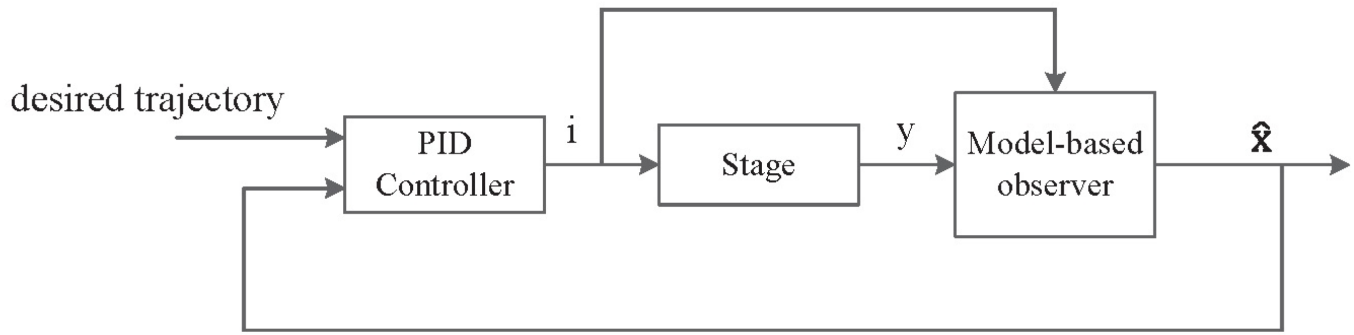
$$K = \begin{bmatrix} 2 \\ 4 \end{bmatrix}$$

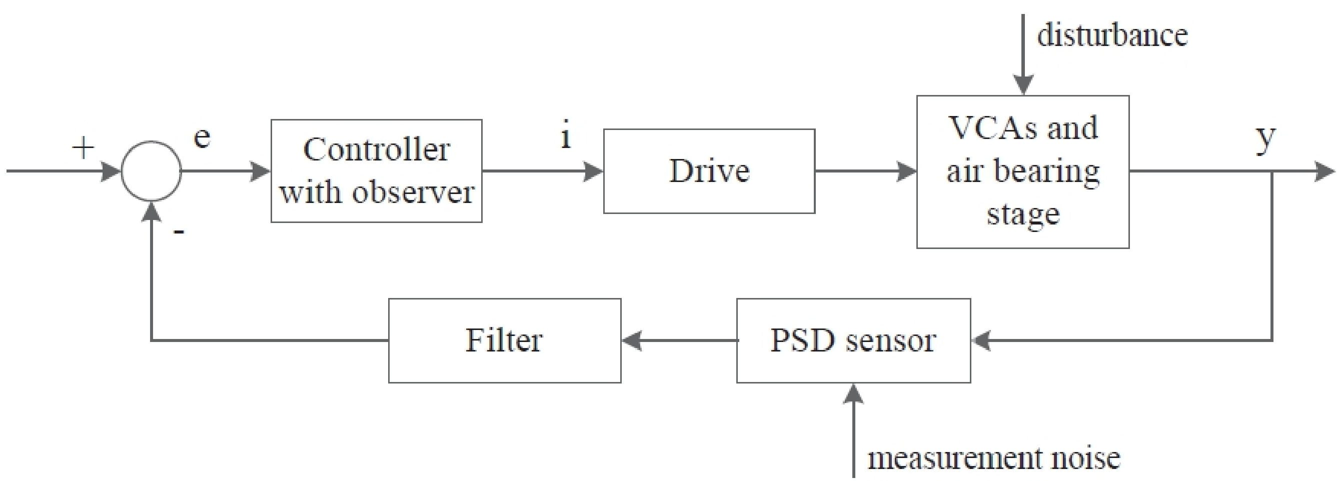
$$\begin{cases} \dot{\hat{X}} = A\hat{X} + B(bi - a) + K(y - \hat{y}) \\ \hat{y} = C\hat{X} \end{cases}$$



Spherical Air Bearing Positioning Stage

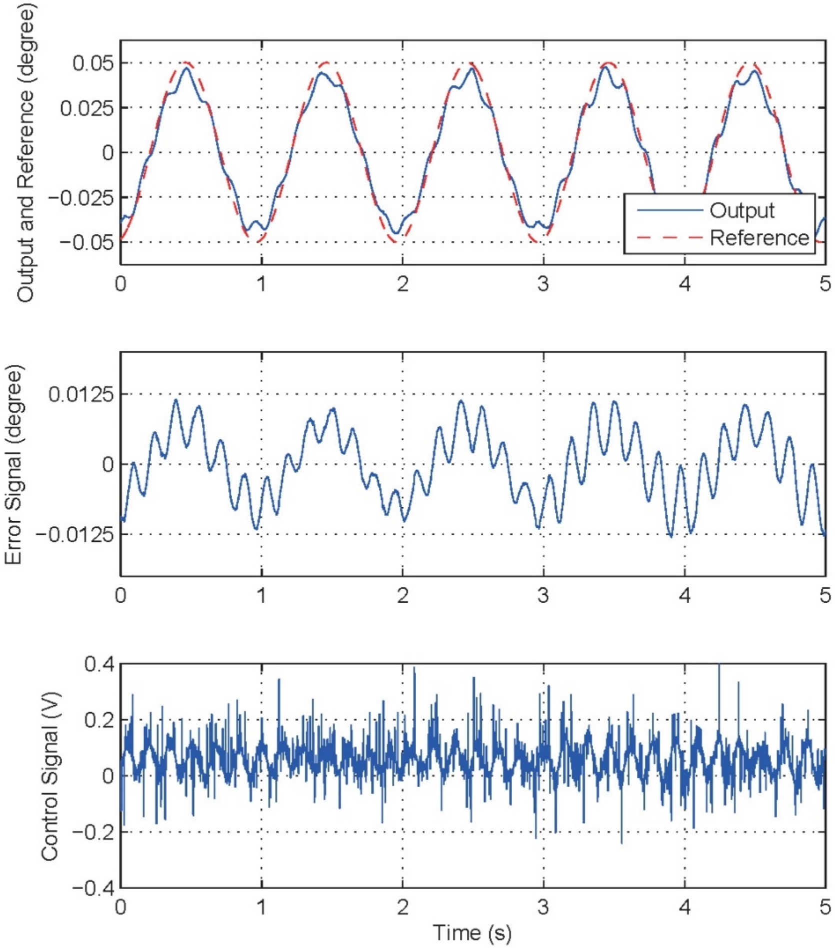
- Observer-based PID Controller





Spherical Air Bearing Positioning Stage

- **Observer-based PID Controller**
  - Max. absolute error: 0.0125deg
  - Comparing with the traditional PID controller, it achieves higher precision and better tracking performance of about 10 times than the traditional one

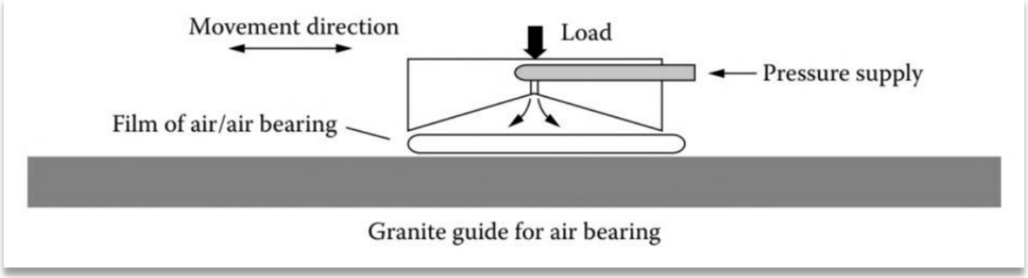


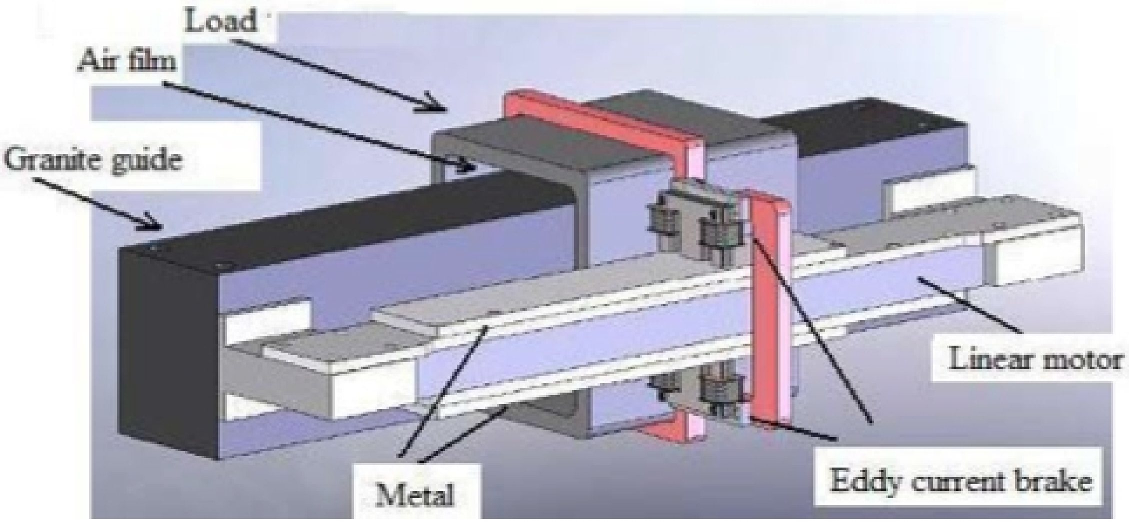
Precision Actuators - Examples

Linear Air Bearing Positioning Stage

Linear Air Bearing Positioning Stage

- 1-DOF
  - Pneumatic system
  - Linear motor
  - Eddy current brake
    - Eddy current damper is introduced in the system, in order to increase the damping rate
  - Controller
    - P control
      + feedback forward
    - Eddy current
      feedback

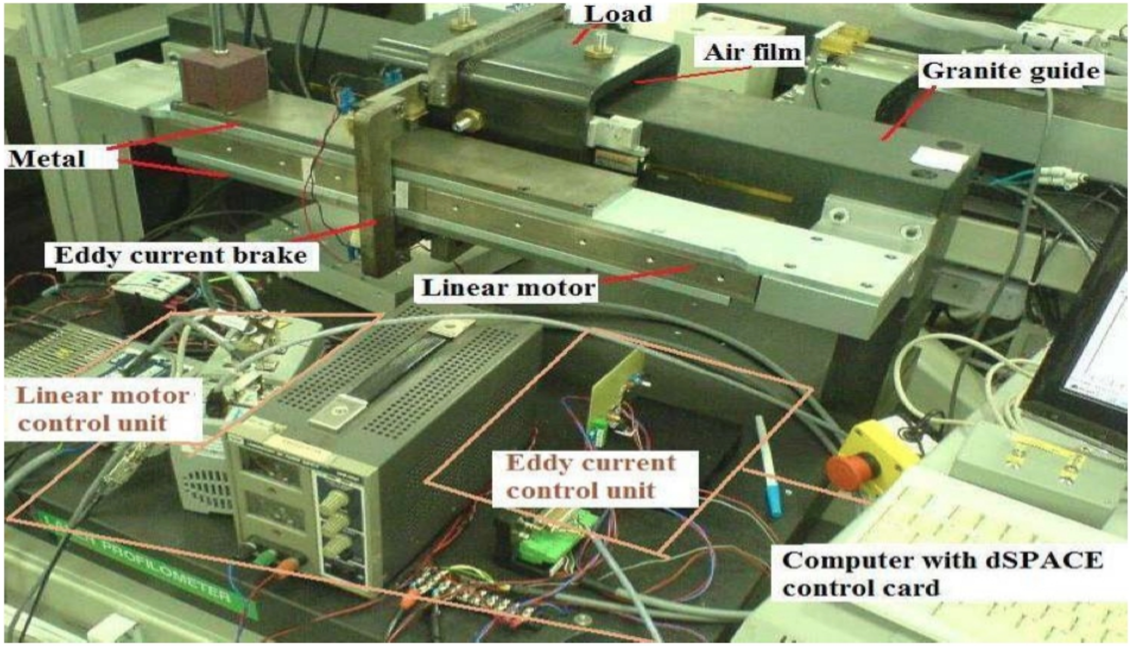


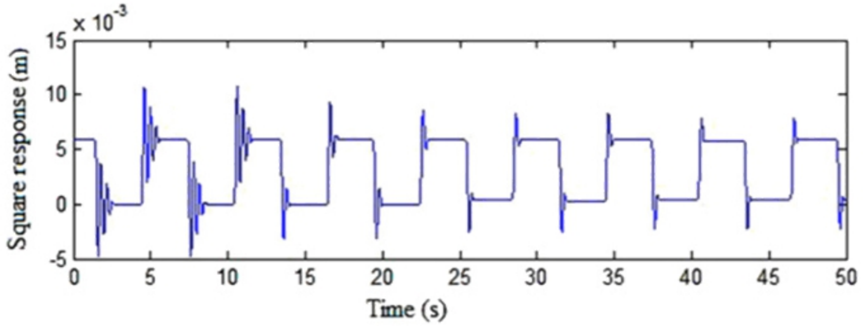


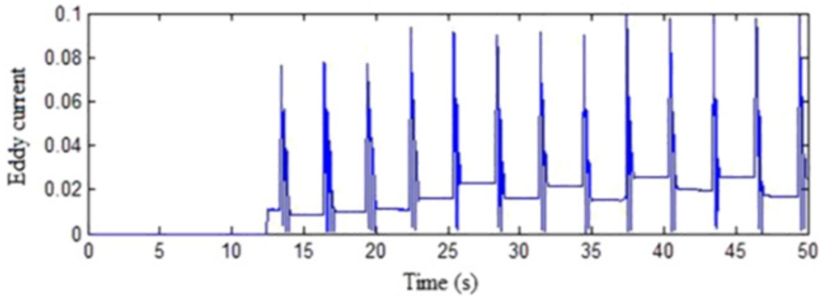
K. K. Tan; S. Huang; R. Yang; C. S. Teo, "Controller design of eddy current braking in an air bearing system," *Automatica*, vol. 48, no. 11, pp.2831-2836, Nov. 2012

Linear Air Bearing Positioning Stage

- 1-DOF
  - System setup
  - Experimental results
    - Tracking error is improved due to the controller
    - The energy used is reduced after the eddy current is applied

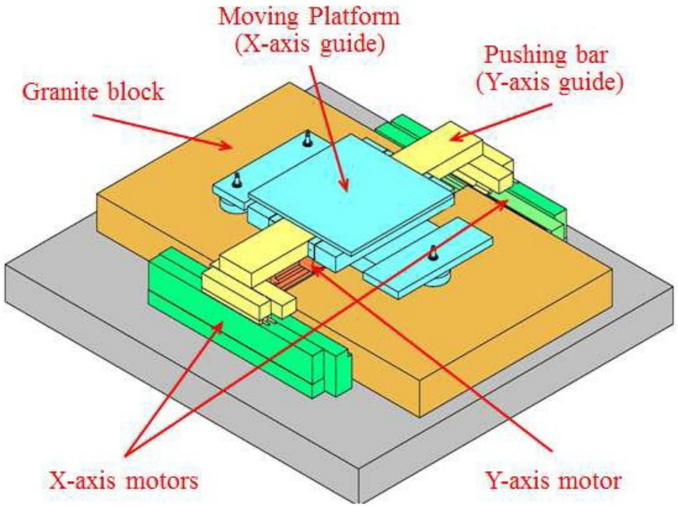






Linear Air Bearing Positioning Stage

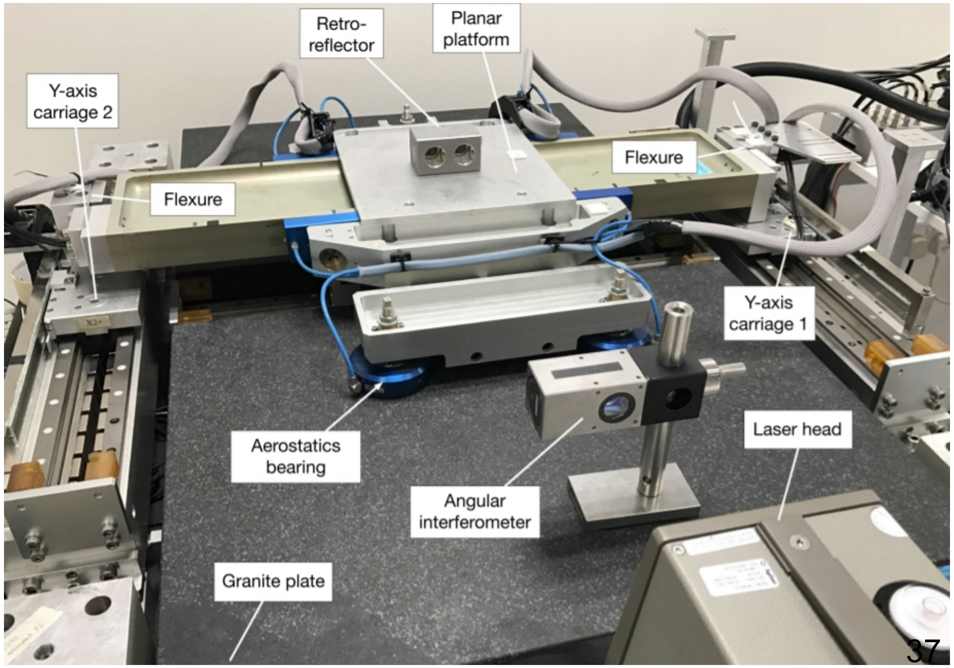
- 2-DOF
  - X-axis (dual-drive H-gantry)
    - Two **parallel** linear motors
    - Linked by flexure
      - *to prevent the damage of joints for its interaxial coupling force*
      - *to allows quick and cost-effective replacement of permanently deflected flexures*
  - Y-axis
    - One linear motor
    - Decoupled design with X-axis
  - Aerostatic bearing



(S.-L. Chen SL; F. Gharib F; C. S. Teo; W. Lin, "Modeling and compensation of flexible modes in 3-DOF H-gantry with decoupling design: a primitive study," *International Conference on Experimental Mechanics 2014* vol. 9302, pp. 930239-1-6, Mar. 2015)

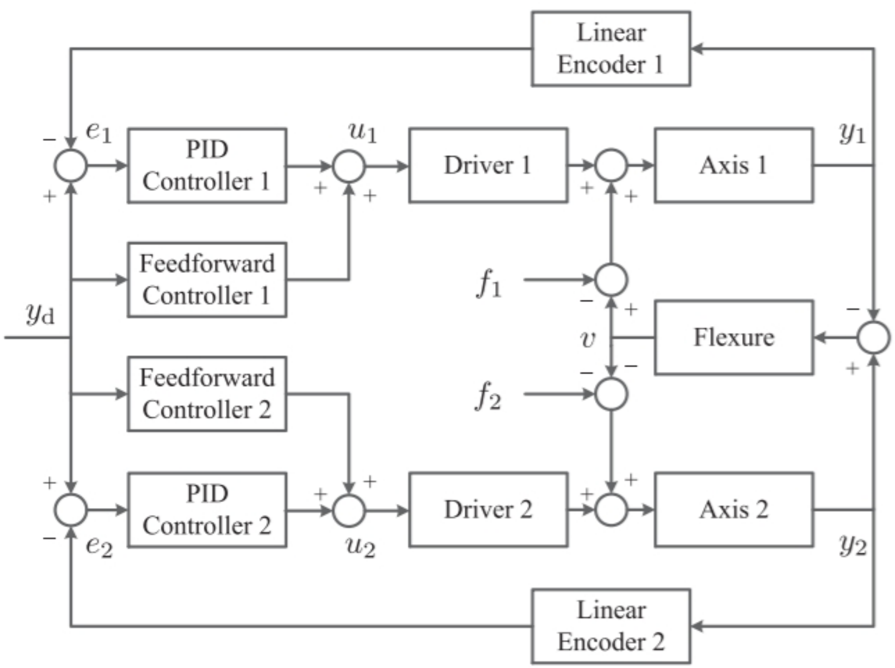
Linear Air Bearing Positioning Stage

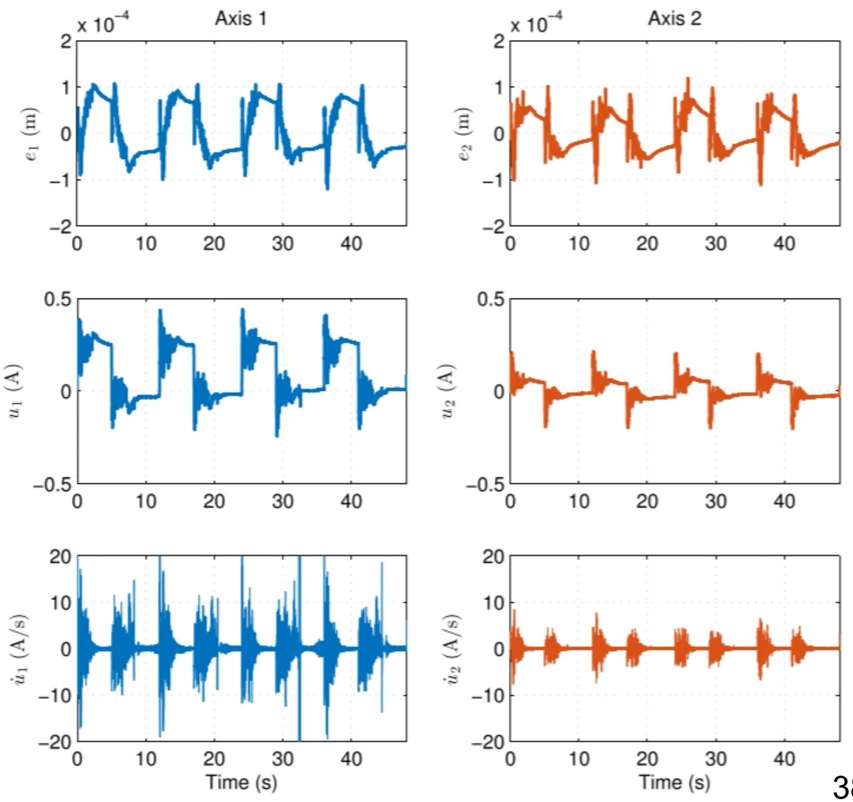
- 2-DOF
  - Controller (X-axis)
    - 2-DOF Decentralized PID Controller
      - *synthesize the gains of both controller at the same time*
        - structural constraint
        - can not use ARE
      - *numerical procedures to obtain the optimal controller gains*



Linear Air Bearing Positioning Stage

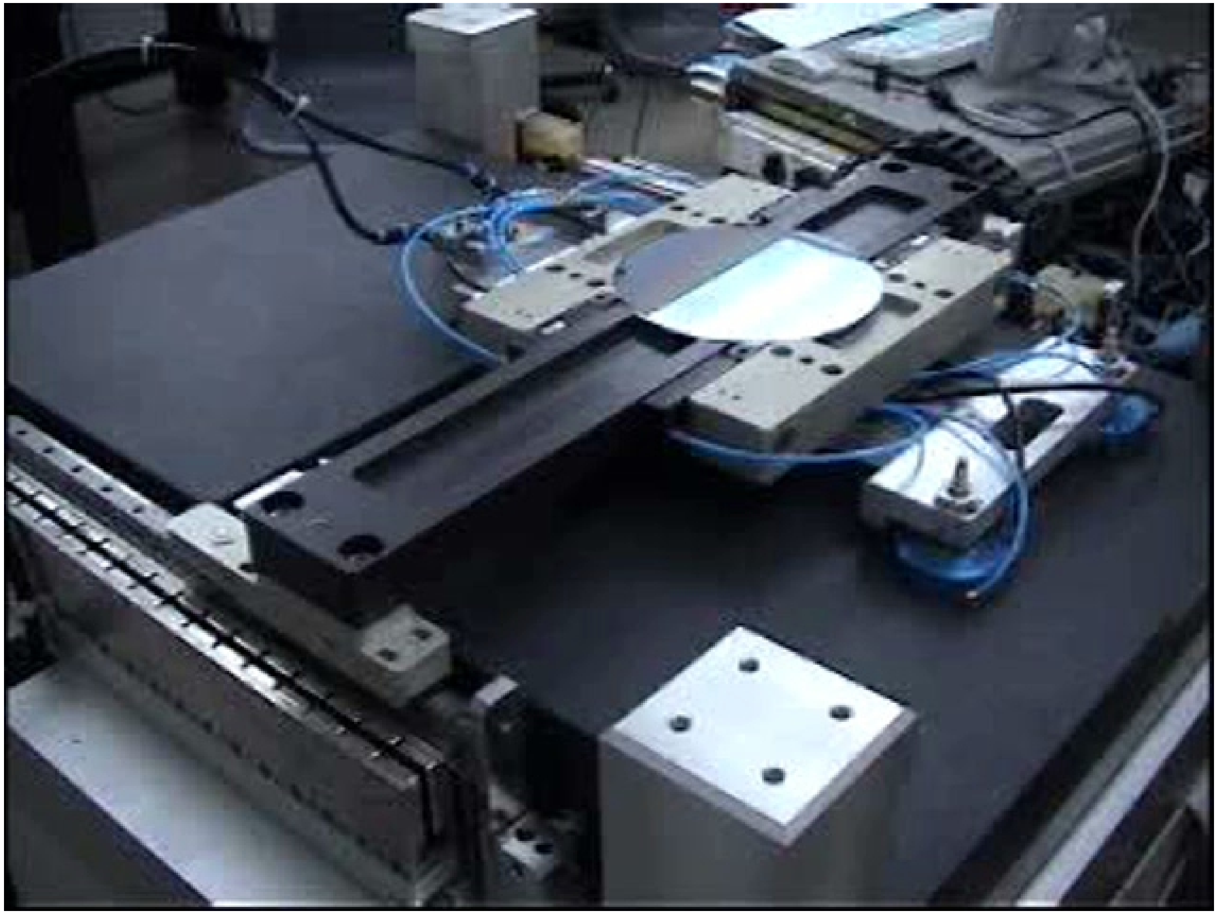
- 2-DOF
  - Experimental results
    - Absolute maximum errors are less than 0.2% of the overall movement distance





Linear Air Bearing Positioning Stage

- 2-DOF Linear Air Bearing Positioning Stage - demo video

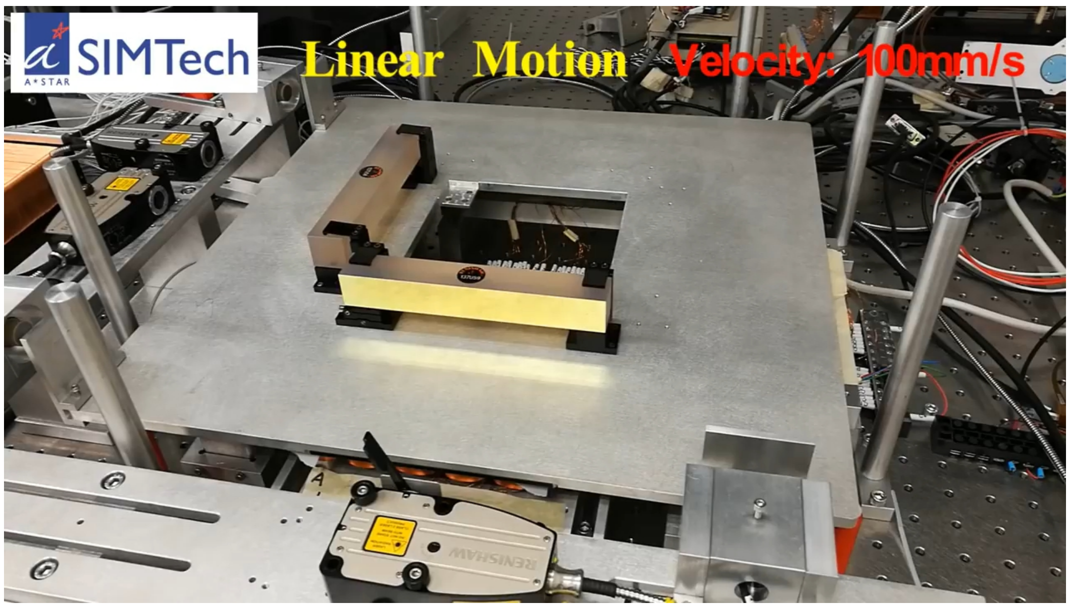


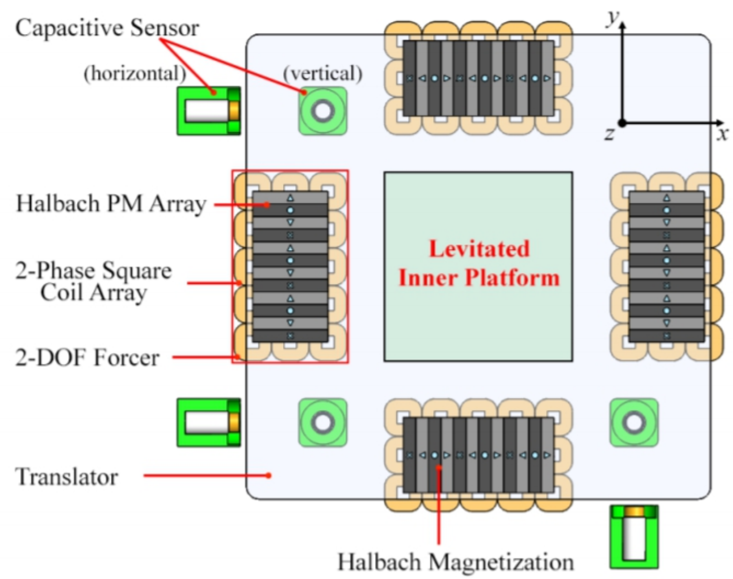
Precision Actuators - Examples

Magnetically Levitated Dual-Stage Positioning System

Magnetically Levitated Positioning System

- 6-DOF maglev primary positioning system
  - contact-less & friction-less, precise

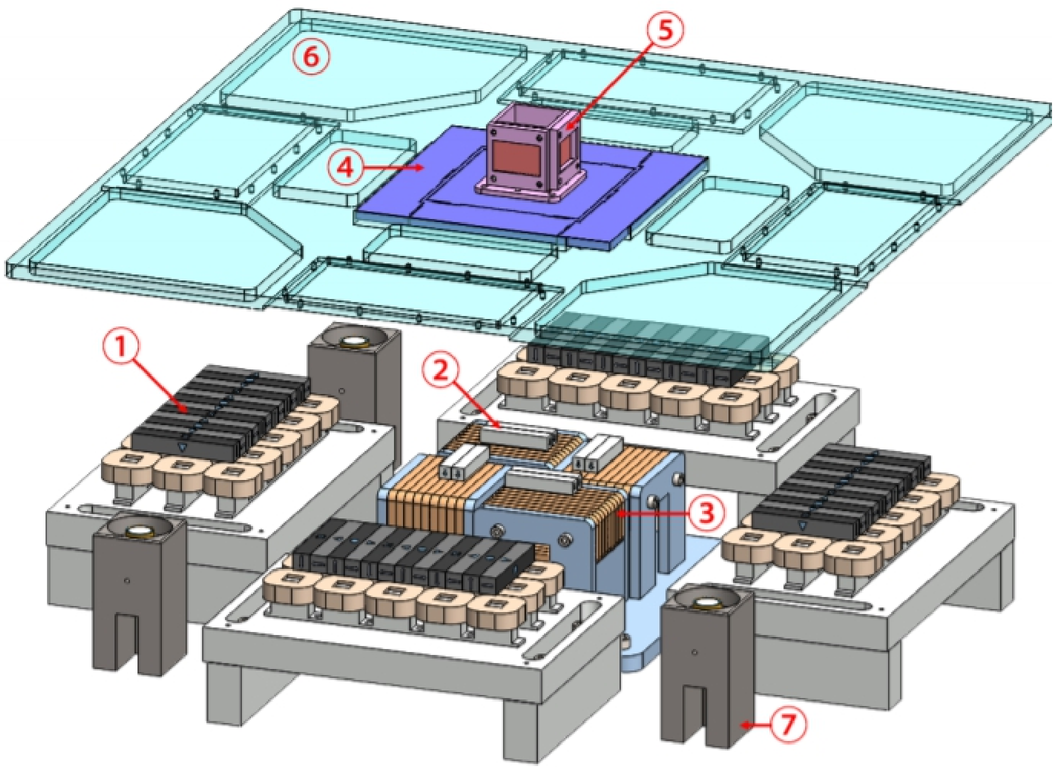




  - but, relatively low servo bandwidth (x high-speed high-frequency?)
    - due to large levitated mass and low nature frequency

Magnetically Levitated Positioning System

- **Dual-Stage Maglev Positioning System**
  - parallel actuation
    - specifically designed flexure-based secondary stage

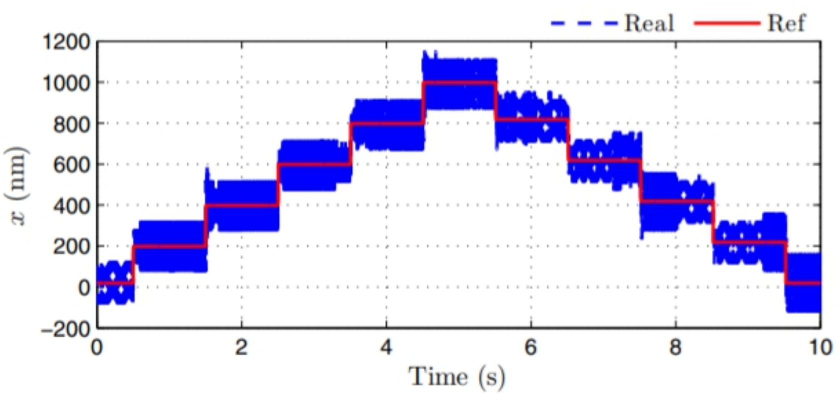


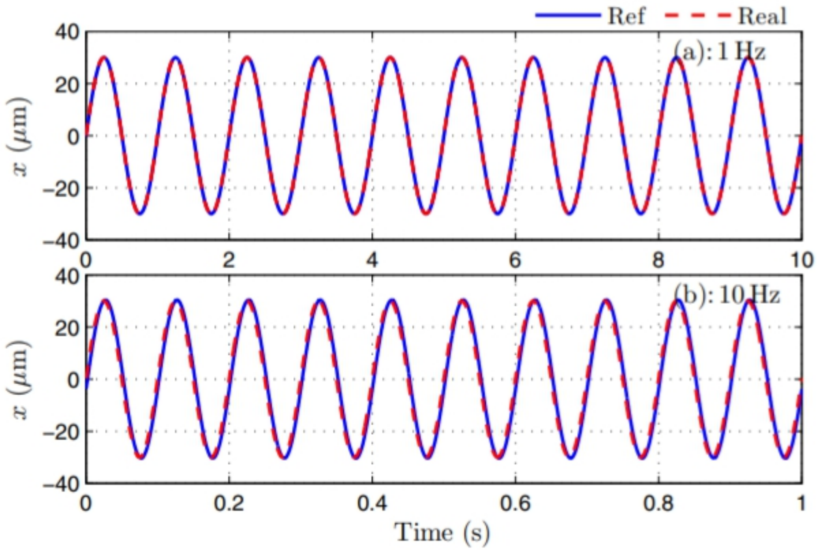
Magnetically Levitated Positioning System

- **Dual-Stage Maglev Positioning System**
  - Controller for the secondary stage
    - PID type second-order controller
  - Experimental results
    - 200 nm steps
    - Trajectory tracking (1 Hz and 10 Hz)

$$K_s(s) = \frac{k_0 s^2 + k_1 s + k_2}{s(s+T_d)} = \frac{n_k(\lambda_k)}{d_k}$$

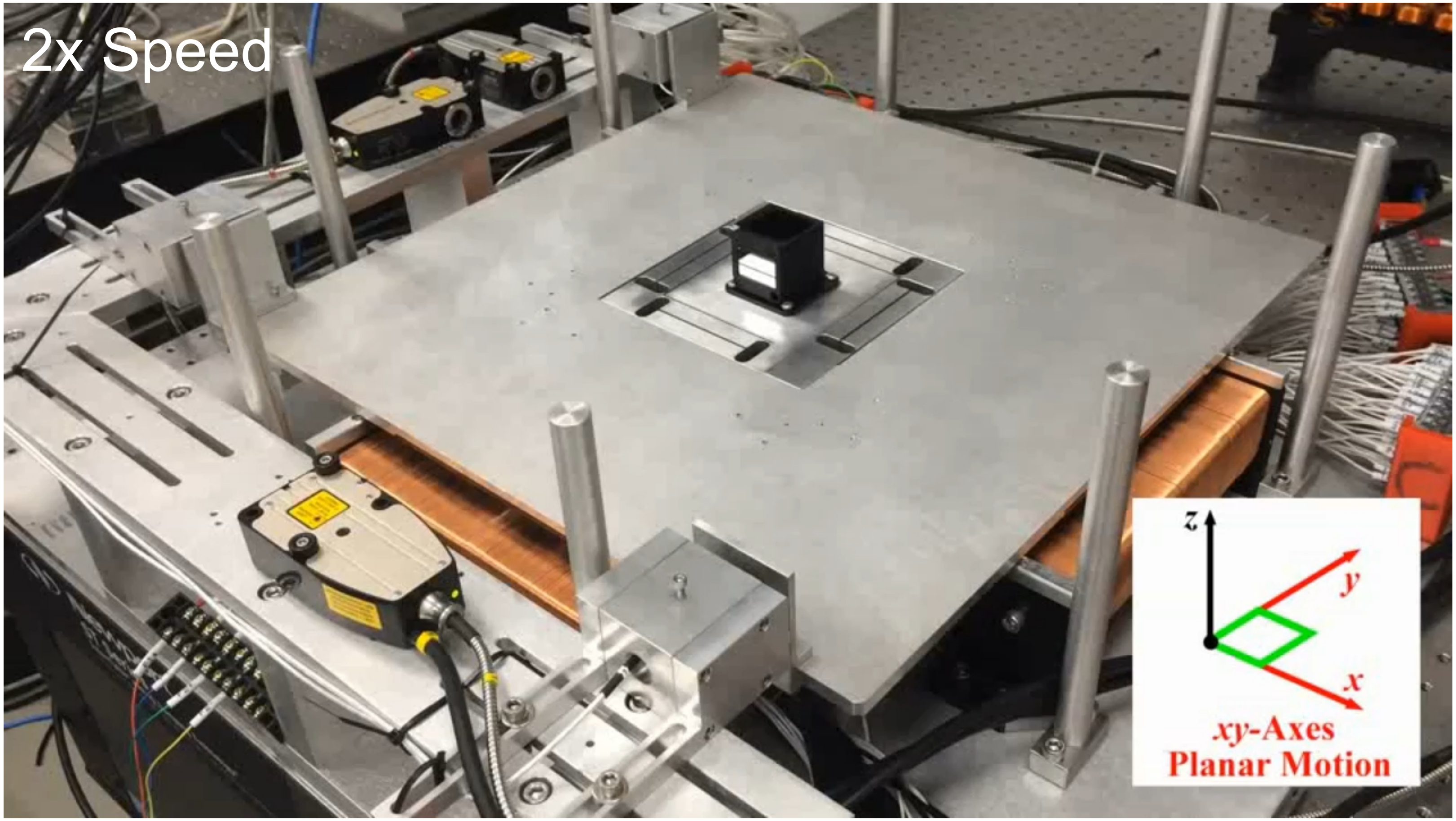
- *MaxAE: 0.44* μm *and 4.18* μm
- *RMSE: 0.28* μm *and 2.93* μm





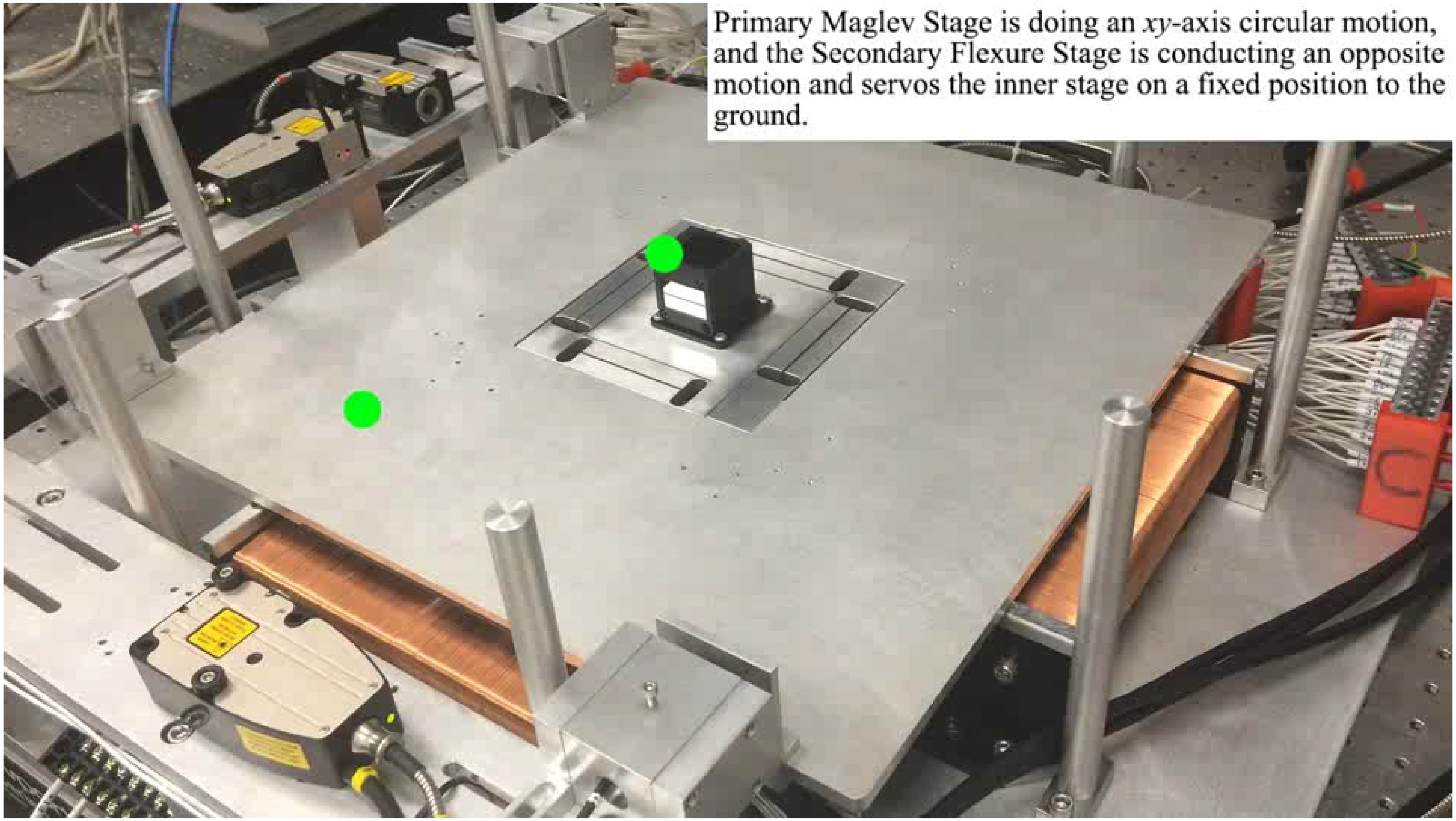
Magnetically Levitated Positioning System

- 6-DOF Maglev Positioning System - demo video



Magnetically Levitated Positioning System

- Dual-Stage Maglev Positioning System - demo video

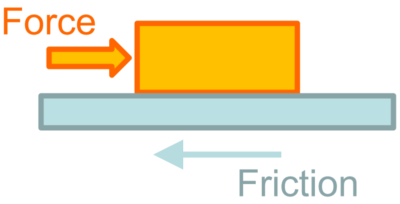


Break

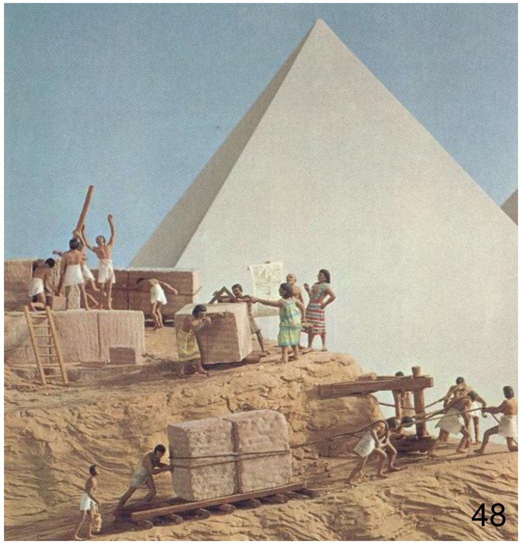
(continue at 19:30)

Friction Compensation

Friction

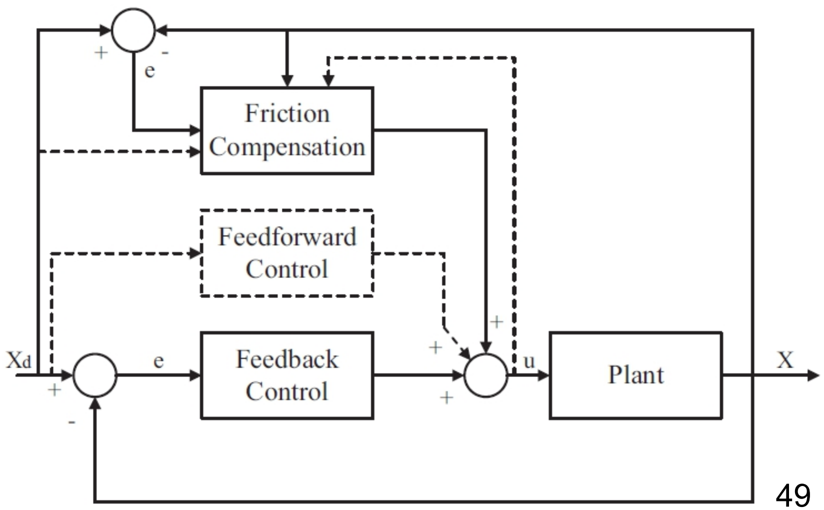


- **What?**
  - Friction is the force resisting the relative motion of two solid objects
  - The limit cycle oscillation generated by friction can cause position errors during steady state, and it also degrades closed-loop performance
  - This phenomena can be observed in **ALL** mechanical systems with moving solid bodies
- **How to reduce friction?**
  - The concept on reducing the frictional effects can be traced back to ancient Egypt
  - Friction compensation is crucial to high precision motion control systems



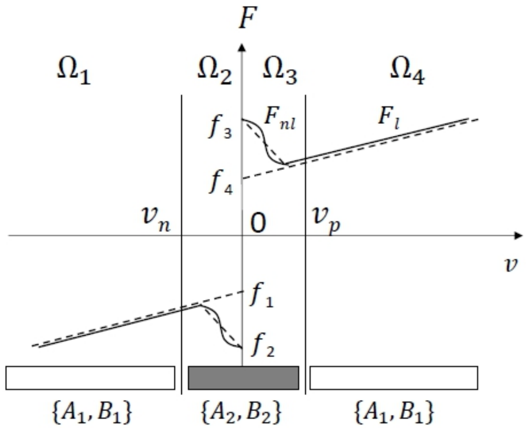
Friction Compensation

- **Basic Idea**
  - The friction compensation is delivered by another loop in the control system which is parallel to the feedback or feedforward control loop
  - The system output and the feedback error will typically serve as the inputs to the friction compensator
  - The compensator's output is then directed as the input to the system for compensating the frictional effects
- **Methods** (two categories)
  - Model-based
  - Model-free



Friction Compensation

- **Model-based Compensation**
  - In the domain of model-based intelligent friction compensation, one of the key prerequisites is the availability of the friction model
    - If an accurate model of the frictional force is available for the specific system, friction compensation can then be achieved with the model
  - Friction Model
    - A **friction model** provides insight into the physical mechanisms of the friction characteristics and serves as a basis for control design purposes
    - Different models:
      - *Classical model*
      - *Time-delay model*
      - *LuGre model*
      - *Generalized Maxwell-slip (GMS) model*



Friction Compensation

- **Model-based Compensation**
  - Classical model $F = f_c \mathrm{sgn}(\dot{x}) + (f_s - f_c)e^{-|\dot{x}/\dot{x}_v|^\delta} + f_v\dot{x}$
    - This model is characterized by a discontinuous relation between the frictional force and velocity, reflecting the Stribeck effects in friction
  - Time-delay model
    - This is a static model developed and adopted in early friction research $F = c_0\dot{x}(t-h) + \frac{c_1}{1 + c_2\dot{x}^2(t-h)}\mathrm{sgn}(\dot{x})$
    - Parameter estimation is not easy
  - LuGre model $\dot{z} = \dot{x} - \sigma_0 \frac{|\dot{x}|}{g(\dot{x})} z,\ F = \sigma_0 z + \sigma_1 \dot{z} + \sigma_2 \dot{x}$
    - A dynamical friction model which is capable of capturing more features of the friction behavior such as stick-slip oscillations and zero-slip displacement $g(\dot{x}) = \alpha_0 + \alpha_1 e^{-(\dot{x}/\dot{x}_v)^2}$
  - Generalized Maxwell-slip (GMS) model
    - The frictional force is the sum of all elementary forces $F = \sum_{i=1}^{N}(k_i z_i(t) + \varrho_i \dot{z}_i(t)) + f_v \dot{x}$

Friction Compensation

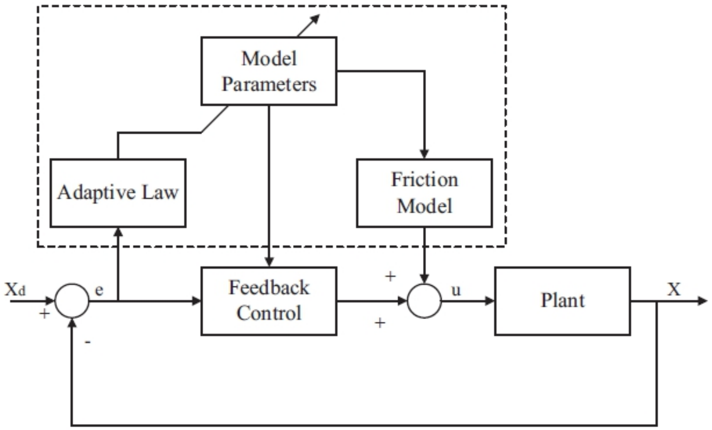
- **Model-based Compensation**
  - Comparison among different models
    - The classical model presents the worst accuracy results for low-velocity tracking
    - The GMS model yields the best results
    - However, the GMS model is more complex than the LuGre model, thereby resulting in a higher level of difficulty in software implementation

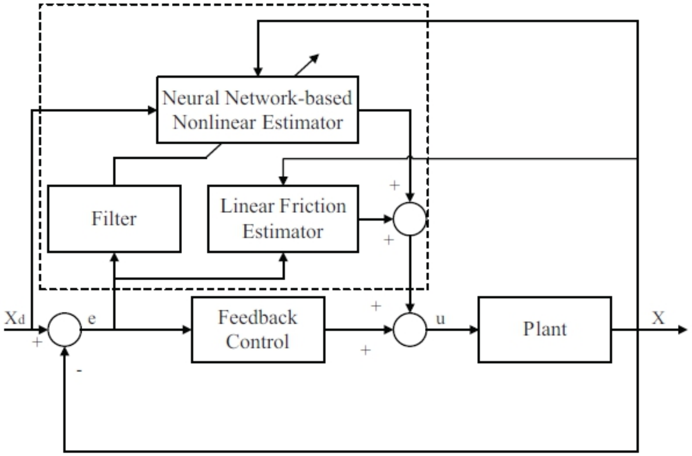
Compensation	RMS error	
	Low stroke	High stroke
No feedforward	1.20	21.1
Classical model	1.10	11.5
LuGre	0.34	9.4
GMS	0.13	9.2

  - Model selection
    - In a practical application, a trade-off will be needed between the performance and the implementation complexity

Friction Compensation

- **Model-based Compensation**
  - Model Parameter Estimation: All the parameters in the models should be estimated for the compensation purpose
    - Adaptive Learning-Based Friction Compensation

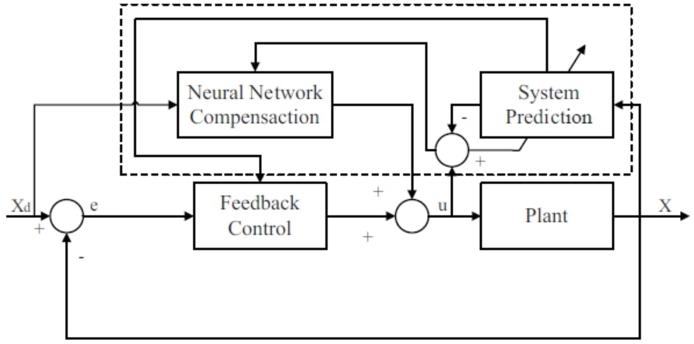




    - Artificial Intelligence System-Based Friction Compensation
      - *Genetic Algorithm-Based Friction Compensation*
        - an off-line optimization process
      - *Machine Learning-Based Friction Compensation*

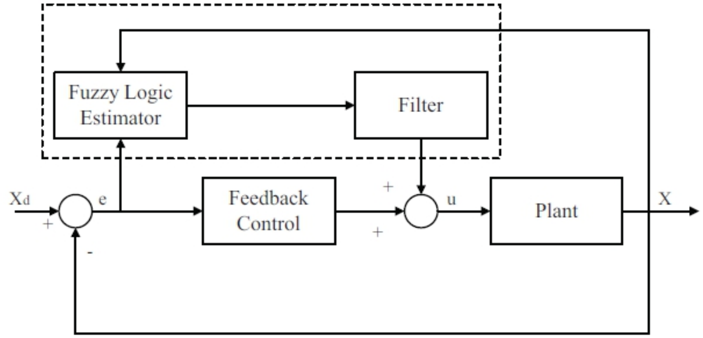
Friction Compensation

- **Model-free Compensation**
  - Although there exist several sophisticated friction models, there is not yet a universally accepted model for friction compensation in different applications
  - To this end, it is necessary to introduce the model-free concept in friction compensation, i.e., compensation scheme **without use of an analytical mathematical model** to represent friction
  - Schemes
    - Neural Network-Based Friction Compensation

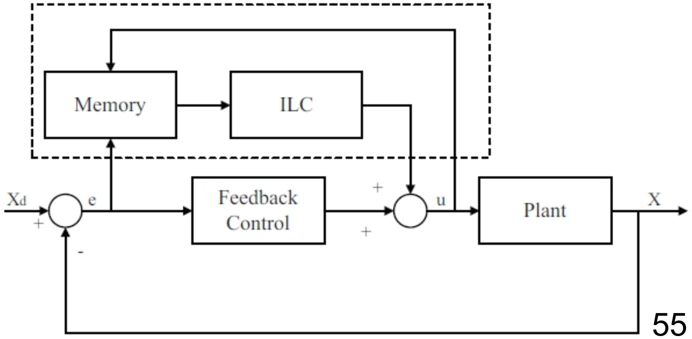


Friction Compensation

- **Model-free Compensation**
  - Schemes
    - Fuzzy Logic Based Friction Compensation



    - Iterative Learning Friction Compensation
      - *When a motion is repetitive in nature, iterative learning control (ILC) can be used as a learning method to control the system*



Friction Compensation

- **Summary**
  - Model-based: relies on a friction model structure
  - Model-free: relax the model requirement; obtain a more accurate estimation on friction; achieve a better compensation performance; but need to consider computational load

Friction Compensation
- Model-based
  - Classical model
  - Time-delay model
  - LuGre model
  - Generalized Maxwell-slip (GMS) model
  - ……

  more complex;
  more accurate;
  combined with adaptive learning, artificial intelligence for parameter estimation
- Model-free
  - Neural Network
  - Fuzzy Logic
  - Iterative Learning
  - ……

  without analytical mathematical model;
  suitable for different applications

Friction Compensation - Examples

Piezoelectric Ultrasonic Motor Stage

Ultrasonic Motor Stage

- **Problem Formulation**
  - Model of single-axis USM

$$\begin{aligned}\ddot{x} &= -a_1\dot{x} - a_0 x + bu - g(x,\dot{x}) + d \\ &= f(x,\dot{x}) + bu - g(x,\dot{x}) + d \\ y &= x\end{aligned}$$

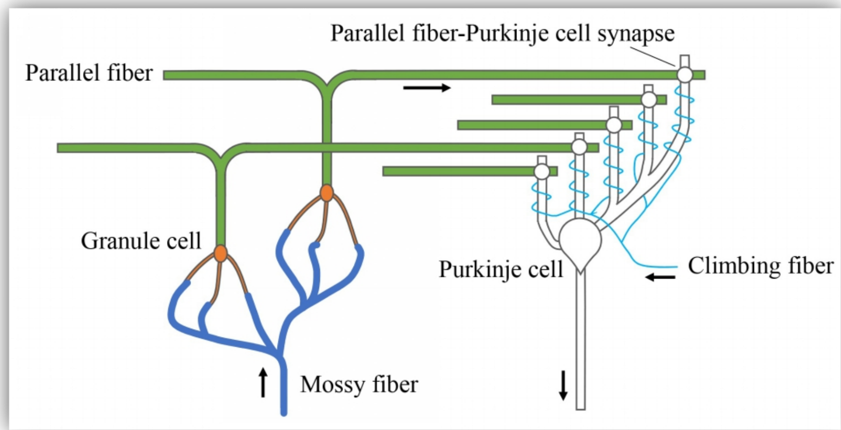
  - If all the system parameters and the information are known or measurable, the system can be well controlled by the following prefect control law

$$u_p = \frac{1}{b}(\ddot{y}_d - f(x,\dot{x}) + g(x,\dot{x}) - d + \boldsymbol{K}\boldsymbol{e})$$

$$\ddot{x} = \ddot{y}_d + \boldsymbol{K}\boldsymbol{e} \quad \Rightarrow \quad \ddot{e} + \boldsymbol{K}\boldsymbol{e} = \ddot{e} + k_d\dot{e} + k_p e = 0 \quad \Rightarrow \quad \boxed{\lim_{t\to\infty} e = 0}$$

Ultrasonic Motor Stage

- **Control Scheme**
  - PID Controller
    - Employed as the main linear controller
  - Cerebellar Model Articulation Controller (CMAC): a cerebellum-inspired intelligent controller
    - Used as the friction compensator

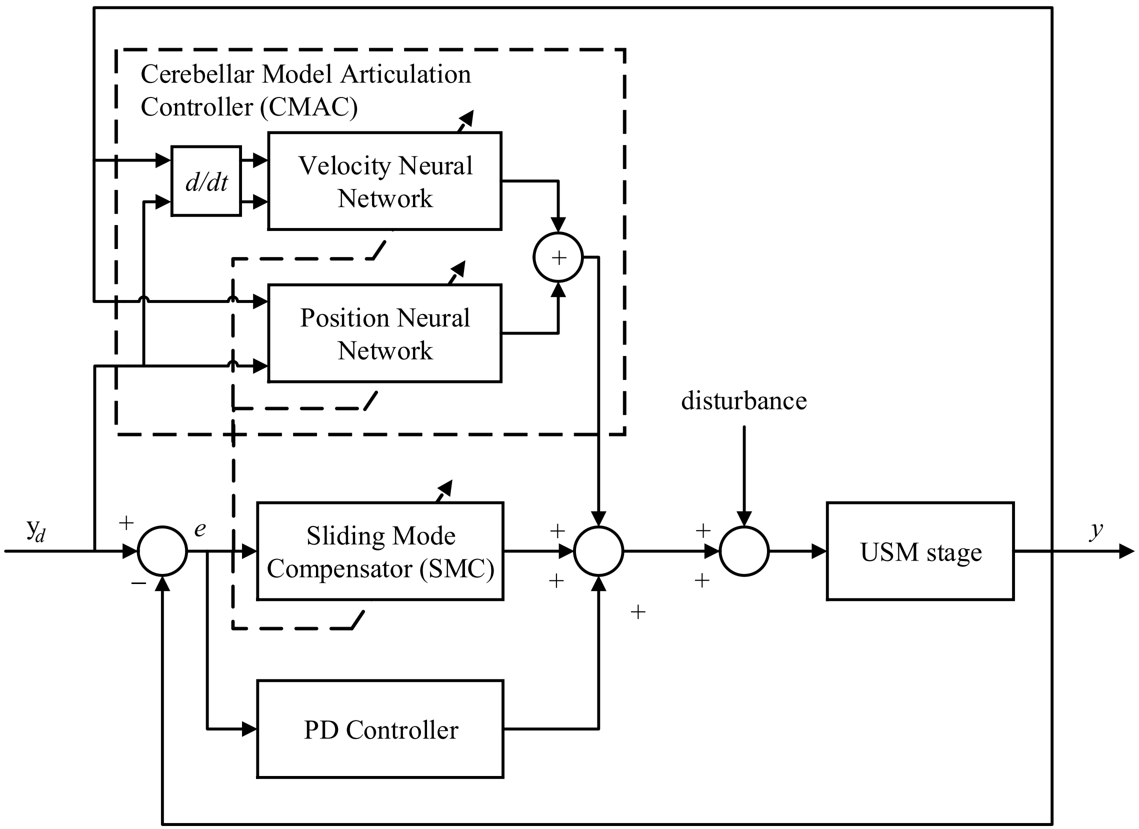


Basic structure of cerebellum

  - Adaptive Sliding Mode Compensator (SMC)
    - Designed as the residual error compensator

Ultrasonic Motor Stage

- **Control Scheme**
  - Control system block diagram



Ultrasonic Motor Stage

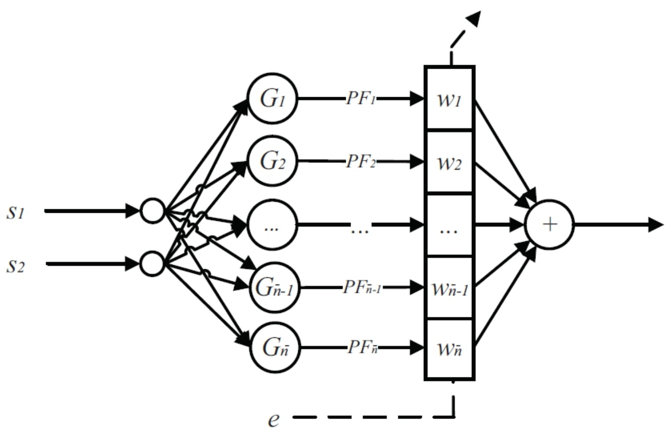
- **Control Scheme**
  - CMAC: it can be mathematically represented by a pair of mappings

$$M \xrightarrow{m_I} G \xrightarrow{m_O} P_w(\hat{\mathbf{w}})$$

    - Input space: the inputs are divided into finite and quantized regions

$$q_i = \frac{(s_{imax} - s_{imin})}{r_i} \quad \text{for } i = 1, 2, 3, 4$$

    - Association cell space: find out the regions needed to be activated corresponding to the current input vectors



$$\varphi_{ij_i}(s_i) = \exp\left[-\frac{(s_i - \mu_{ij_i})^2}{\sigma_{ij_i}^2}\right] \quad \text{for } j_i = 1, 2, \ldots, n_i$$

$$\text{and } i = 1, 2, 3, 4$$

Ultrasonic Motor Stage

- Control Scheme
  - CMAC
    - Association cell space: for 2-dimentional (2D) case

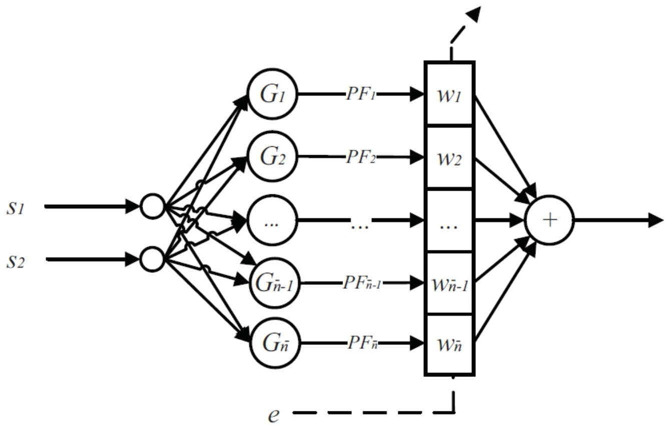
$$G_l^p(\mathbf{s}) = \prod_{i=1}^{2} \varphi_{ij_i}(s_i) = \varphi_{1j_1}(s_1)\varphi_{2j_2}(s_2)$$

for $j_i = 1, 2, ..., n_i$ and $l = 1, 2, ..., n^p$

and

$$G_l^v(\mathbf{s}) = \prod_{i=3}^{4} \varphi_{ij_i}(s_i) = \varphi_{1j_1}(s_3)\varphi_{2j_2}(s_4)$$

for $j_i = 1, 2, ..., n_i$ and $l = 1, 2, ..., n^v$



$$\begin{aligned}
\phi(\mathbf{s}) &= [\phi_1 \otimes \phi_2 \quad \phi_3 \otimes \phi_4] \\
&= [G_1^p \quad G_2^p \quad \ldots \quad G_{\bar{n}}^p \quad G_1^v \quad G_2^v \quad \ldots \quad G_{\bar{n}}^v]^T \\
&= [G_1 \quad G_2 \quad \ldots \quad G_{\bar{n}} \quad G_{\bar{n}+1} \quad G_{\bar{n}+2} \quad \ldots \quad G_n]^T
\end{aligned}$$

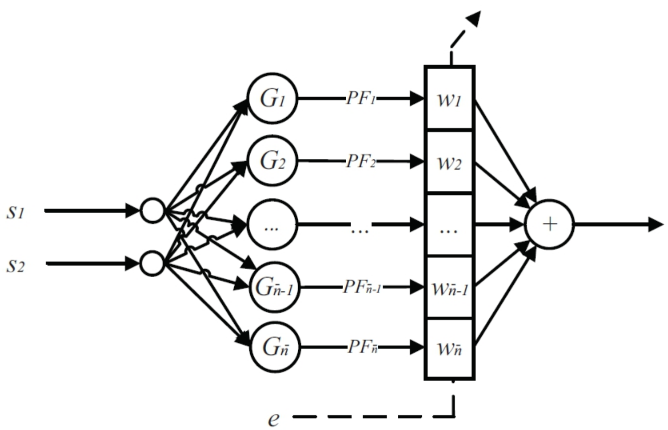
Ultrasonic Motor Stage

- Control Scheme
  - CMAC
    - Output space: the sum of the activated weights in the weight memory

$$u_c = \sum_{l=1}^{n} \hat{w}_l G_l = \hat{\boldsymbol{w}}^T \phi$$

    - Update law

$$\dot{\hat{\boldsymbol{w}}} = \beta \boldsymbol{e}^T P \boldsymbol{B} \phi$$



$$A^T P + PA + Q = 0$$

$$A = \begin{bmatrix} 0 & 1 \\ -k_p & -k_d \end{bmatrix}$$

Ultrasonic Motor Stage

- Control Scheme
  - SMC
    - Control law $$u_s = \hat{\kappa}\mathrm{sign}(\boldsymbol{e}^T P\boldsymbol{B})$$
    - Update law

$$\dot{\hat{\kappa}} = \begin{cases} \rho|\boldsymbol{e}^T P\boldsymbol{B}|, & \text{if } p(\hat{\kappa}) \le 0 \\ \rho|\boldsymbol{e}^T P\boldsymbol{B}|, & \text{if } p(\hat{\kappa}) \ge 0 \text{ and } \bar{p}(\hat{\kappa})\rho|\boldsymbol{e}^T P\boldsymbol{B}| \le 0 \\ \left[I - \frac{p(\hat{\kappa})\bar{p}(\hat{\kappa})\bar{p}(\hat{\kappa})^T}{||\bar{p}(\hat{\kappa})||^2}\right]\rho|\boldsymbol{e}^T P\boldsymbol{B}|, & \text{otherwise} \end{cases}$$

with

$$p(\hat{\kappa}) = \frac{\hat{\kappa}^T\hat{\kappa} - \kappa_M^2}{\upsilon^2 + 2\upsilon\kappa_M}$$

$$\bar{p}(\hat{\kappa}) = \frac{\partial p(\hat{\kappa})}{\partial\hat{\kappa}}$$

    - This projection has the following property

$$\mathrm{Proj}(\rho|\boldsymbol{e}^T P\boldsymbol{B}|, \hat{\kappa}) \ge \rho|\boldsymbol{e}^T P\boldsymbol{B}|$$

Ultrasonic Motor Stage

- **Control Scheme**
  - Stability analysis
    - Assumption: for the CMAC, there exists a set of optimal weights that minimizing the difference between the CMAC and the desired perfect controller. Hence, we have the minimal approximation error

$$\varepsilon = u_p - \boldsymbol{w}^T \boldsymbol{\phi}$$

      which is unknown but bounded $|\varepsilon| \leq \epsilon$
    - Define the following Lyapunov function

$$V = \frac{1}{2}\boldsymbol{e}^T P \boldsymbol{e} + \frac{1}{2\beta}\tilde{\boldsymbol{w}}^T \tilde{\boldsymbol{w}} + \frac{1}{2\rho}\tilde{\kappa}^2$$

$$\Downarrow$$

$$\dot{V} = \frac{1}{2}\dot{\boldsymbol{e}}^T P \boldsymbol{e} + \frac{1}{2}\boldsymbol{e}^T P \dot{\boldsymbol{e}} - \beta^{-1}\tilde{\boldsymbol{w}}^T \dot{\hat{\boldsymbol{w}}} - \rho^{-1}\tilde{\kappa}\dot{\hat{\kappa}}$$

Ultrasonic Motor Stage

- Control Scheme
  - Stability analysis $V \geq 0$

$$\dot{V} = \frac{1}{2}\dot{\boldsymbol{e}}^T P \boldsymbol{e} + \frac{1}{2}\boldsymbol{e}^T P \dot{\boldsymbol{e}} - \beta^{-1}\tilde{\boldsymbol{w}}^T \dot{\hat{\boldsymbol{w}}} - \rho^{-1}\tilde{\kappa}\dot{\hat{\kappa}}$$

$$\begin{aligned}
\dot{V} =& \frac{1}{2}\boldsymbol{e}^T(A^T P + PA)\boldsymbol{e} + \boldsymbol{e}^T P\boldsymbol{B}(\delta - u_s) - \boldsymbol{e}^T P\boldsymbol{B}\tilde{\boldsymbol{w}}^T\phi \\
& - \rho^{-1}\tilde{\kappa}\dot{\hat{\kappa}} \\
=& -\frac{1}{2}\boldsymbol{e}^T Q\boldsymbol{e} + \boldsymbol{e}^T P\boldsymbol{B}(\varepsilon - u_s) - \rho^{-1}\tilde{\kappa}\dot{\hat{\kappa}} \\
\leq& -\frac{1}{2}\lambda_{min}\boldsymbol{e}^T\boldsymbol{e} + \boldsymbol{e}^T P\boldsymbol{B}(\varepsilon - u_s) - \rho^{-1}\tilde{\kappa}\dot{\hat{\kappa}}
\end{aligned}$$

$$\boxed{\dot{V} \leq -\frac{1}{2}\lambda_{min}||\boldsymbol{e}||^2 \leq 0}$$

$$\begin{aligned}
\dot{V} \leq& -\frac{1}{2}\lambda_{min}\boldsymbol{e}^T\boldsymbol{e} + \boldsymbol{e}^T P\boldsymbol{B}[\varepsilon - \hat{\kappa}\mathrm{sign}(\boldsymbol{e}^T P\boldsymbol{B})] \\
& - \rho^{-1}\tilde{\kappa}\mathrm{Proj}(\rho|\boldsymbol{e}^T P\boldsymbol{B}|, \hat{\kappa}) \\
\leq& -\frac{1}{2}\lambda_{min}\boldsymbol{e}^T\boldsymbol{e} + |\boldsymbol{e}^T P\boldsymbol{B}|(|\varepsilon| - \kappa)
\end{aligned}$$

Ultrasonic Motor Stage

- **Control Scheme**
  - Stability analysis

$$\lim_{t\to\infty}\int_0^t \frac{1}{2}\lambda_{min}||\boldsymbol{e}||^2 d\tau \le V(0) - V(\infty) \le V(0)$$

    - By virtue of **Barbalat's lemma**, we can conclude that

$$\lim_{t\to\infty} ||\boldsymbol{e}|| = 0$$

  - To reduce the chattering phenomenon induced by the sign function, the saturation function is used

$$u_s = \hat{\kappa}\mathrm{sat}(\boldsymbol{e}^T P\boldsymbol{B})$$

where

$$\mathrm{sat}(\boldsymbol{e}^T P\boldsymbol{B}) = \begin{cases} \mathrm{sign}(\boldsymbol{e}^T P\boldsymbol{B}), & \text{if } |\boldsymbol{e}^T P\boldsymbol{B}/\xi| > 1 \\ \boldsymbol{e}^T P\boldsymbol{B}/\xi, & \text{if } |\boldsymbol{e}^T P\boldsymbol{B}/\xi| \le 1 \end{cases}$$

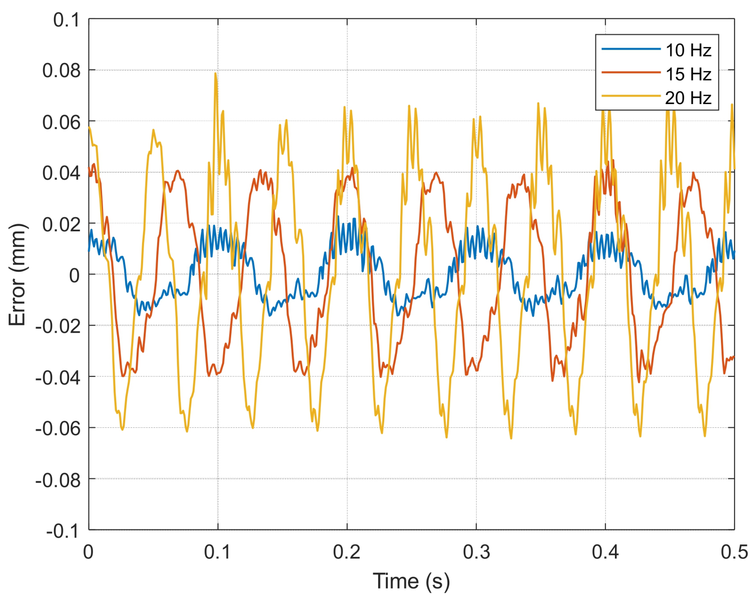
- **Overall controller**

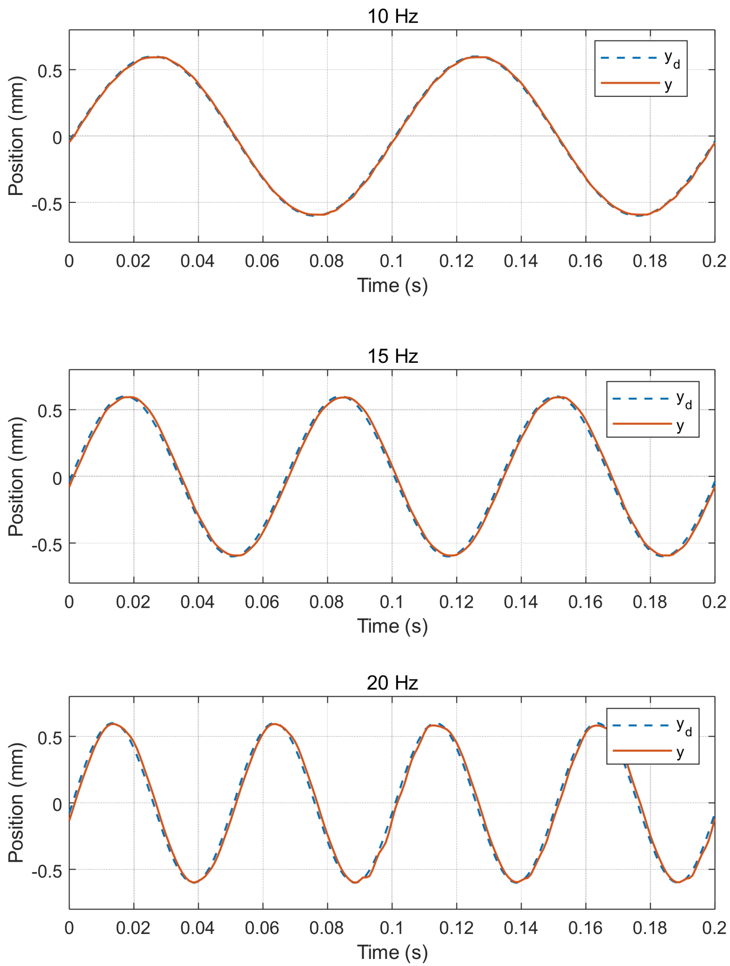
$$u = u_c + u_s = \hat{\boldsymbol{w}}^T \phi + \hat{\kappa}\mathrm{sat}(\boldsymbol{e}^T P\boldsymbol{B})$$

Ultrasonic Motor Stage

- **Experimental Results**
  - Sine wave tracking
    - Without disturbance

Motions	MaxAE (mm)		RMSE (mm)	
	[11]	Proposed	[11]	Proposed
10 Hz	0.0483	0.0226	0.0286	0.0098
15 Hz	0.0689	0.0447	0.0428	0.0279
20 Hz	0.0964	0.0786	0.0582	0.0389



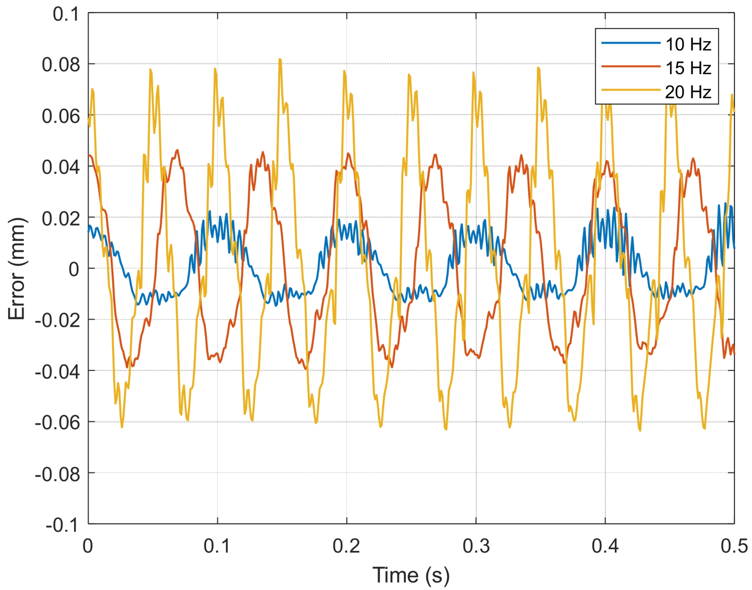


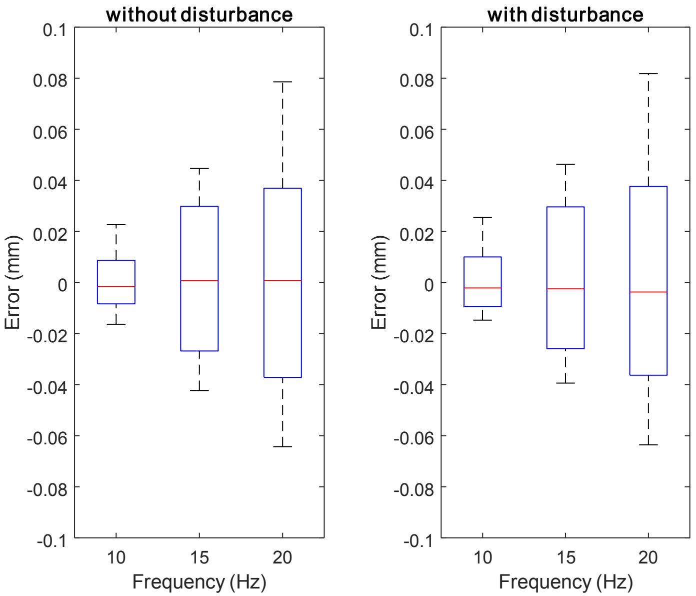
Ultrasonic Motor Stage

- **Experimental Results**
  - Sine wave tracking
    - With disturbance
  - Summary
    - Good tracking performance
    - Guaranteed robustness

Motions	MaxAE (mm)		RMSE (mm)	
	[11]	Proposed	[11]	Proposed
10 Hz	0.0483	0.0226	0.0286	0.0098
15 Hz	0.0689	0.0447	0.0428	0.0279
20 Hz	0.0964	0.0786	0.0582	0.0389

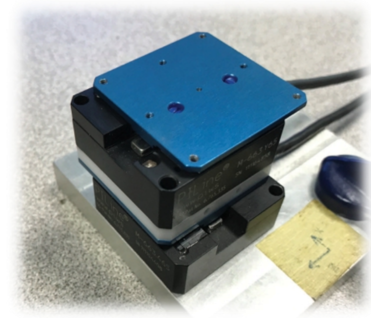
Motions	MaxAE (mm)	RMSE (mm)
	Proposed Controller	Proposed Controller
10 Hz	0.0254	0.0106
15 Hz	0.0463	0.0281
20 Hz	0.0818	0.0419

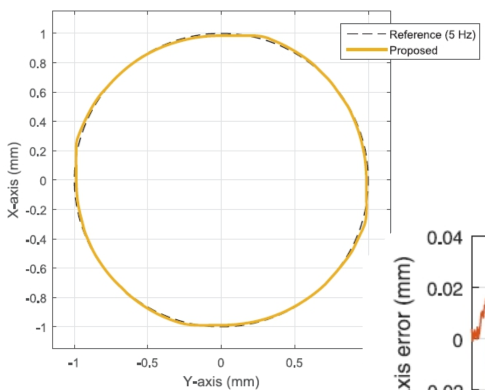


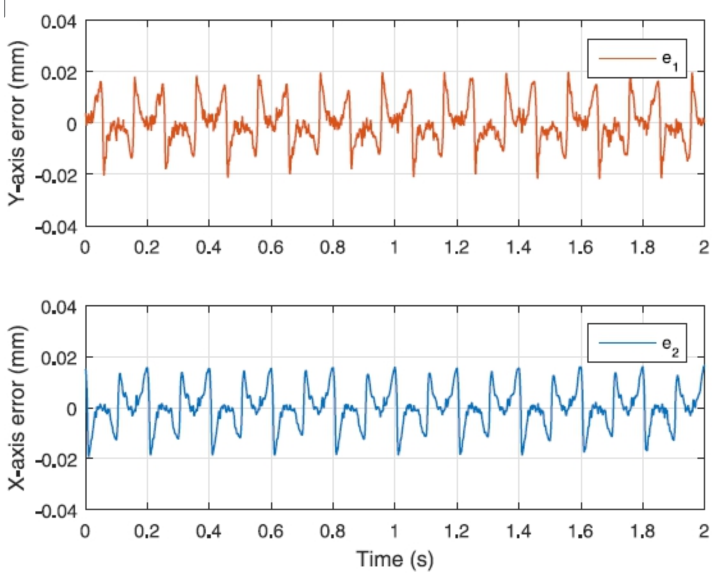


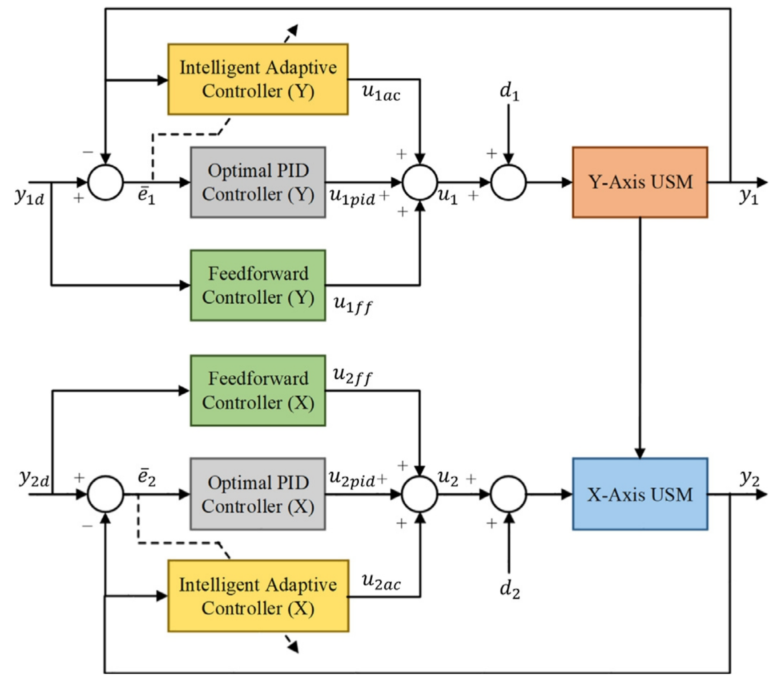
Ultrasonic Motor Stage

- **Experimental Results (2-DOF)**
  - Motion control for a USM driven X-Y stage (2-DOF)
  - Circular motion (1 mm, 5 Hz)



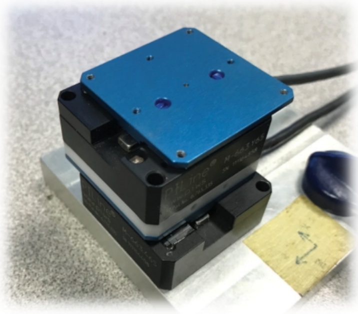


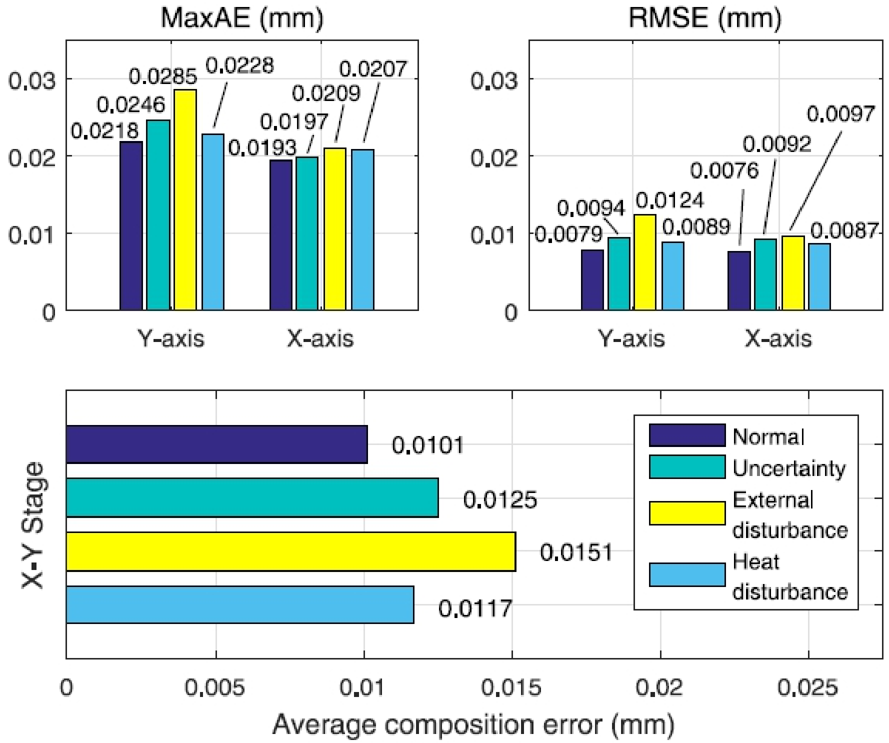




Ultrasonic Motor Stage

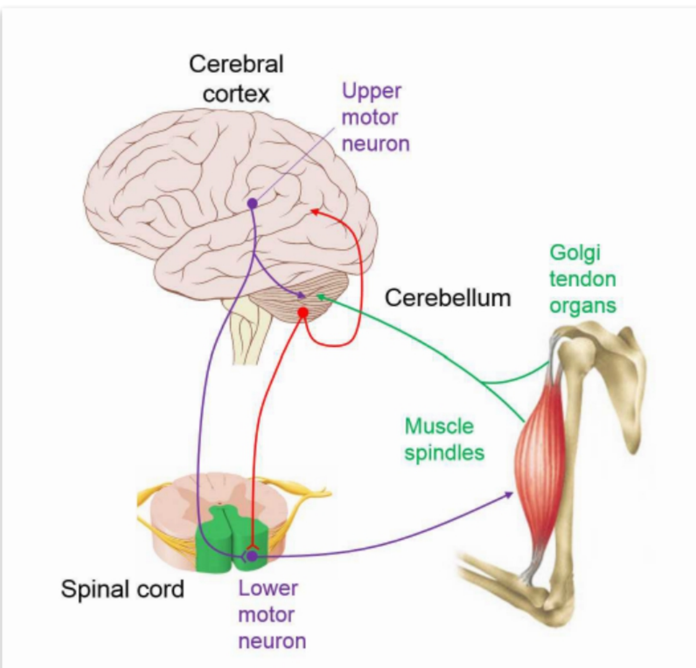
- **Experimental Results (2-DOF)**
  - subjected to uncertainty and disturbance
    - Tracking errors are still within 3% of the trajectory amplitude

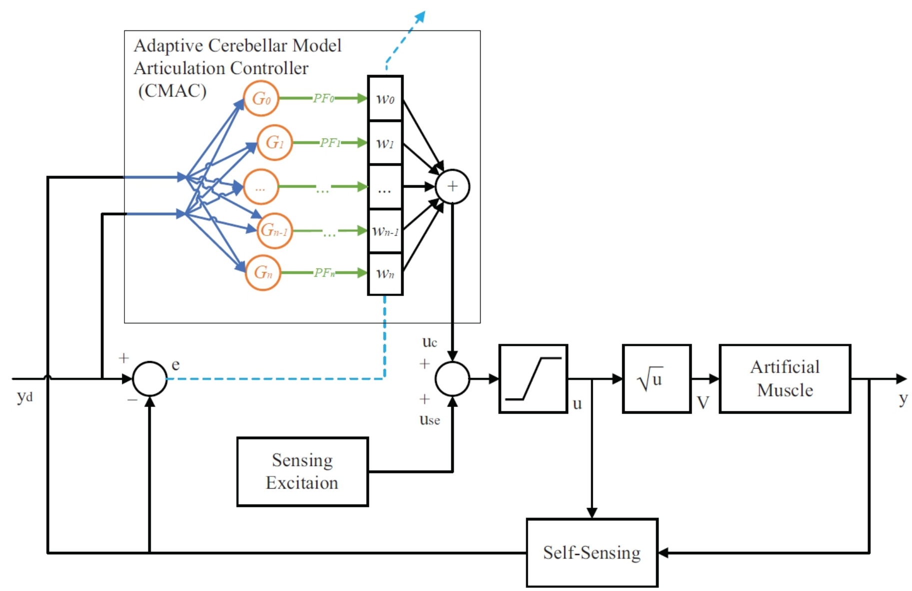




CMAC - Other Applications (I)

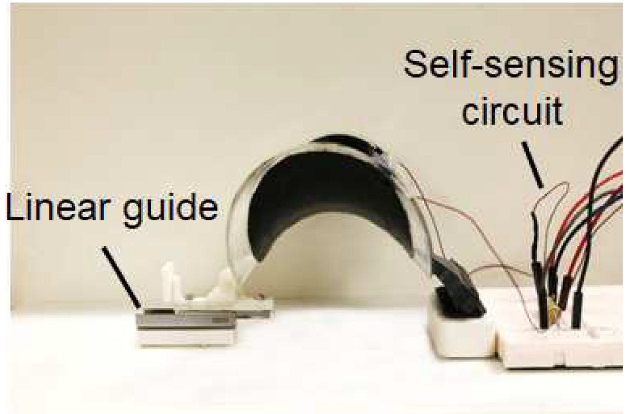
- **Soft Robotics: Dielectric Elastomer Actuator (DEA)**
  - Bio-muscle vs. Artificial muscle (DEA)
  - Golgi tendon & Muscle spindles vs. Self-sensing
  - Cerebellar cortex vs. Cerebellum Model Articulation Controller

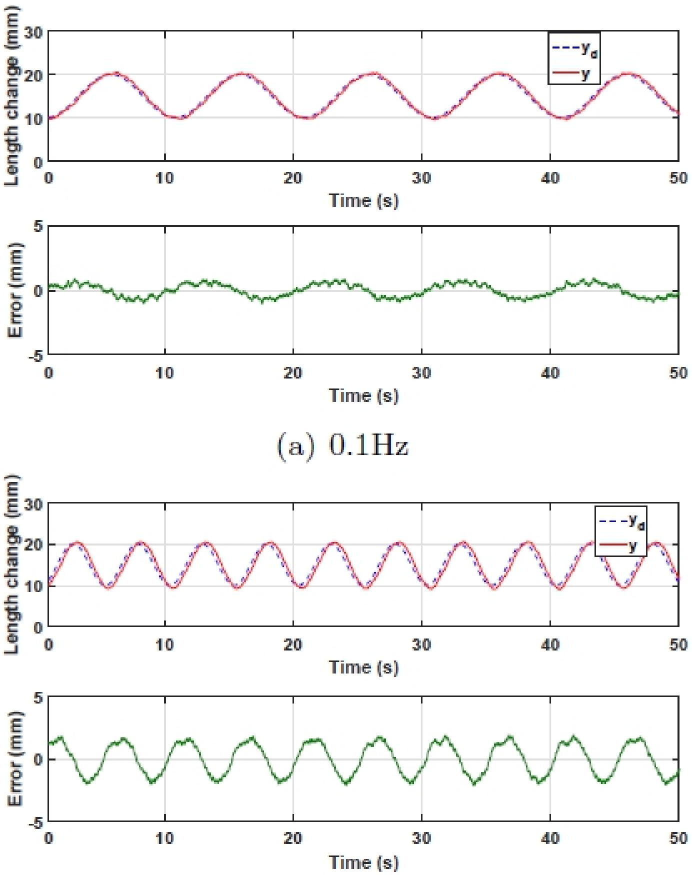




CMAC - Other Applications (I)

- Soft Robotics: Dielectric Elastomer Actuator (DEA)





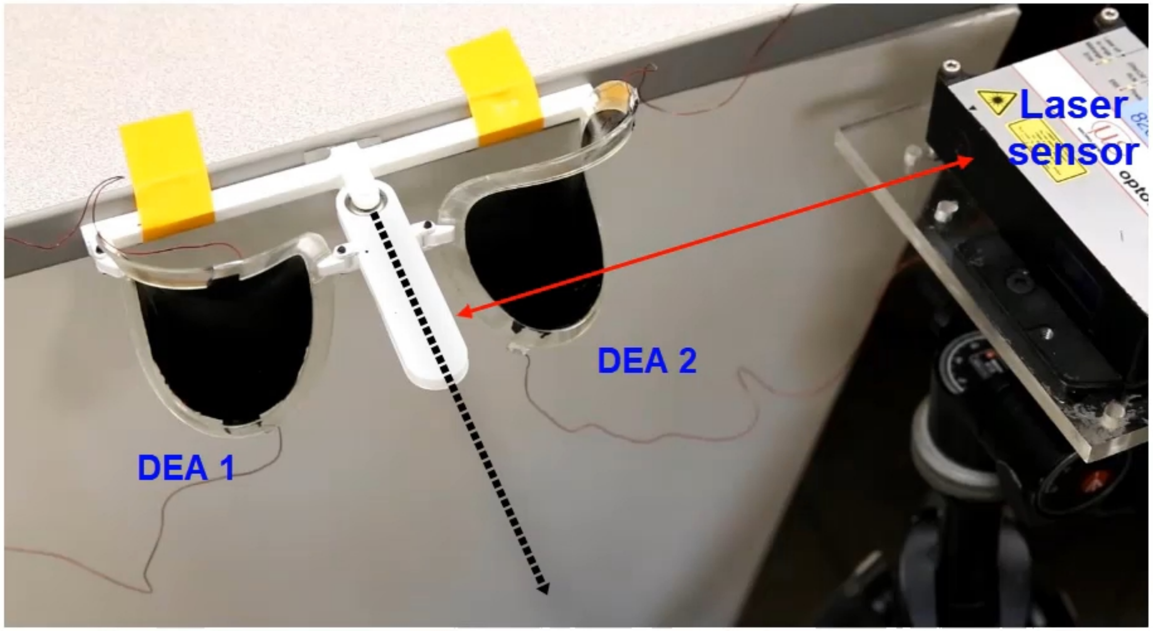
(a) 0.1Hz

(b) 0.2Hz

CMAC - Other Applications (I)

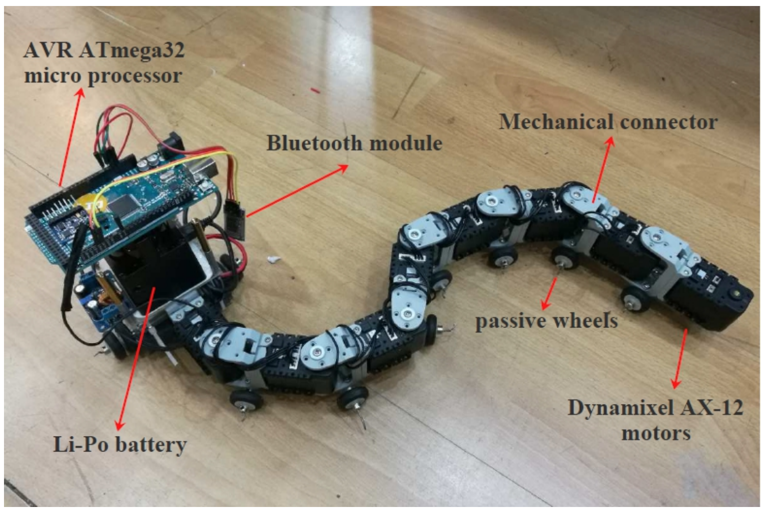
- Antagonistic Soft Robot - demo video

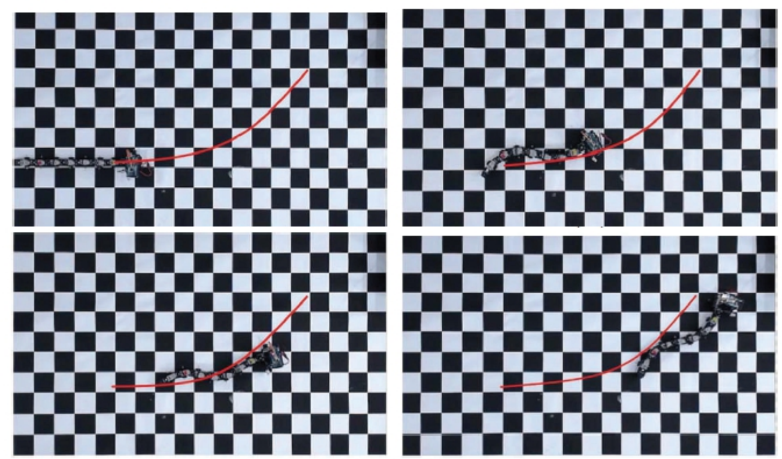
Experimental setup

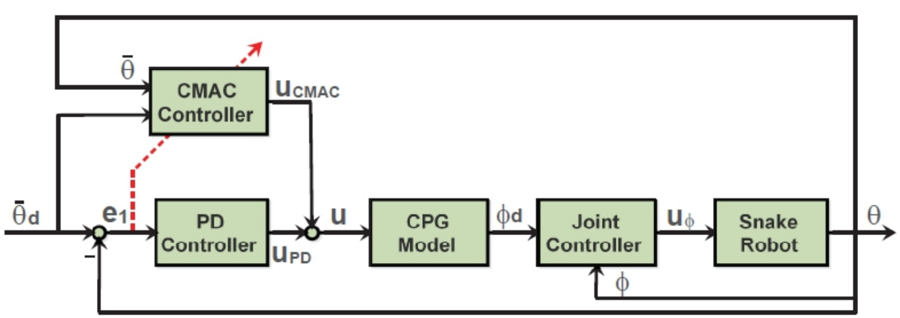


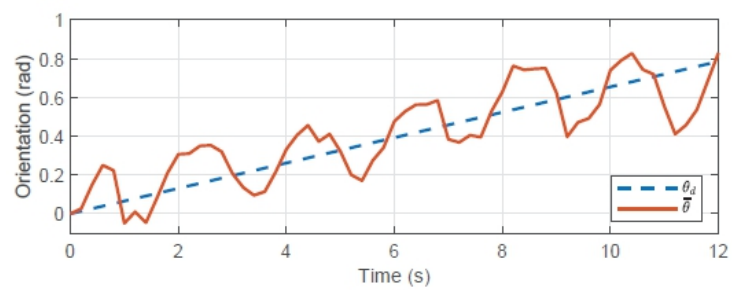
CMAC - Other Applications (II)

- **Bioinspired Robotics: Snake Robot**
  - Steering motion control



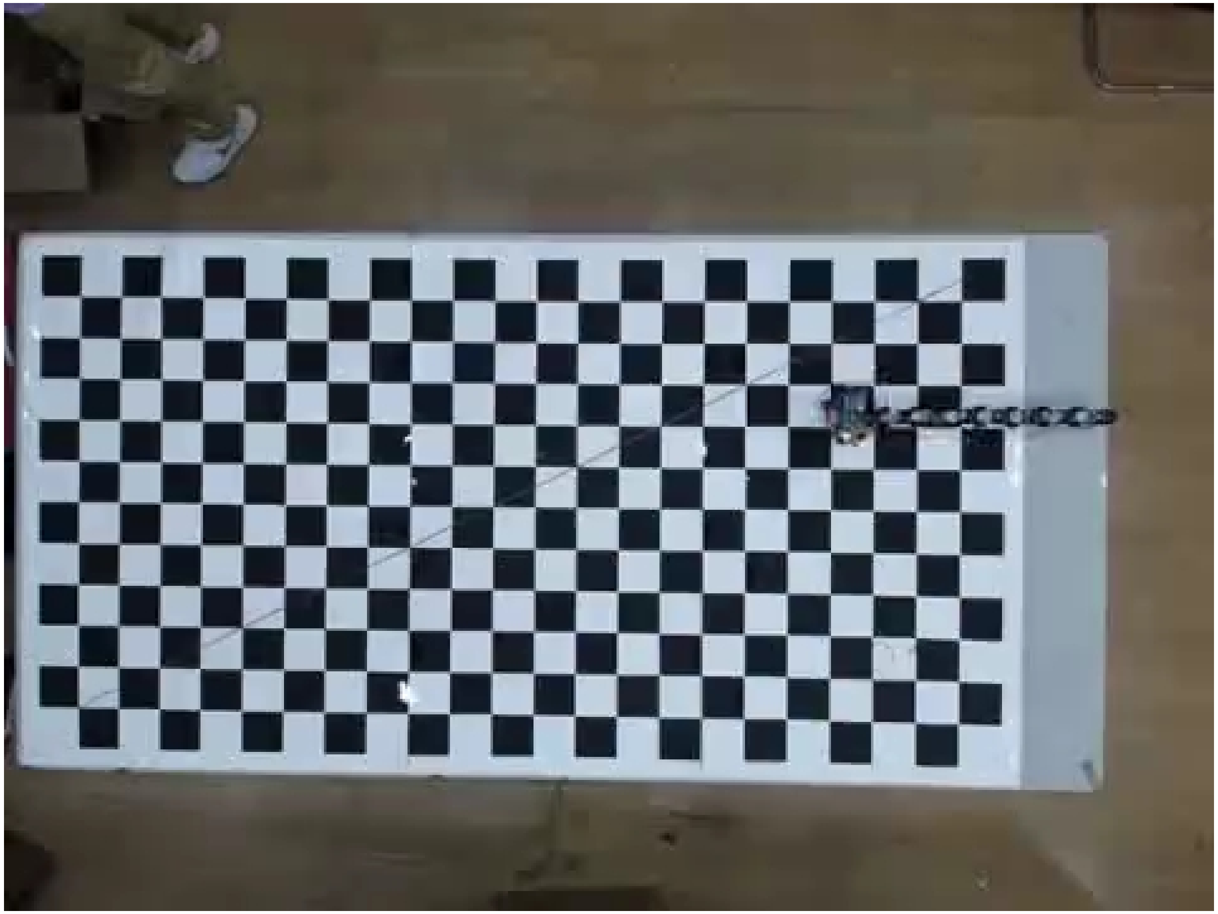






CMAC - Other Applications (II)

- Snake Robot - demo video



Summary

- **Precision Actuators (linear motion)**
  - Direct-drive technology
    - Permanent Magnet Linear Motor (PMLM)
    - Voice Coil Actuator (VCA)
    - Piezoelectric Actuator (PA)
  - Friction-less bearings
    - Air bearing (a type of Fluid bearing)
    - Magnetic bearing
    - Flexure bearing
  - Examples
- **Friction Compensation**
  - Basic concepts
  - Main methods
    - Model-based
    - Model-free
  - Examples

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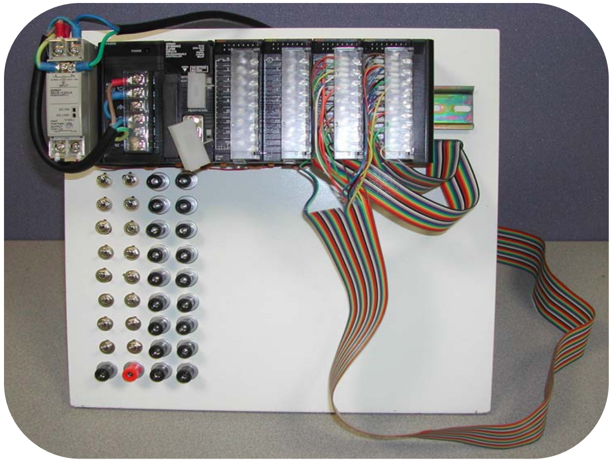
Industrial Control Systems

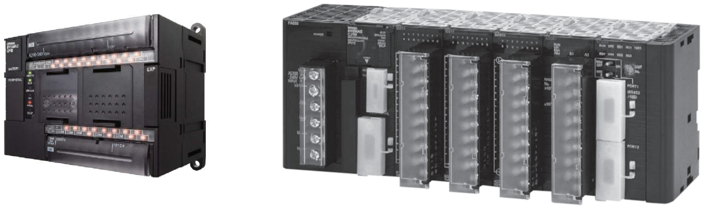
Programmable Logic Controller (PLC)

- **Overview**
  - **Programmable Logic Controller (PLC)** is a digitally operating electronic system, designed for use in an industrial environment, which uses a programmable memory for the internal storage of user-oriented instructions for implementing specific functions such as logic, sequencing, timing, counting and arithmetic, to control, through digital or analogue inputs and outputs, various types of machines or processes (IEC 61131-1)
  - **PLC** is an industrial digital computer which is adapted for the control of manufacturing processes

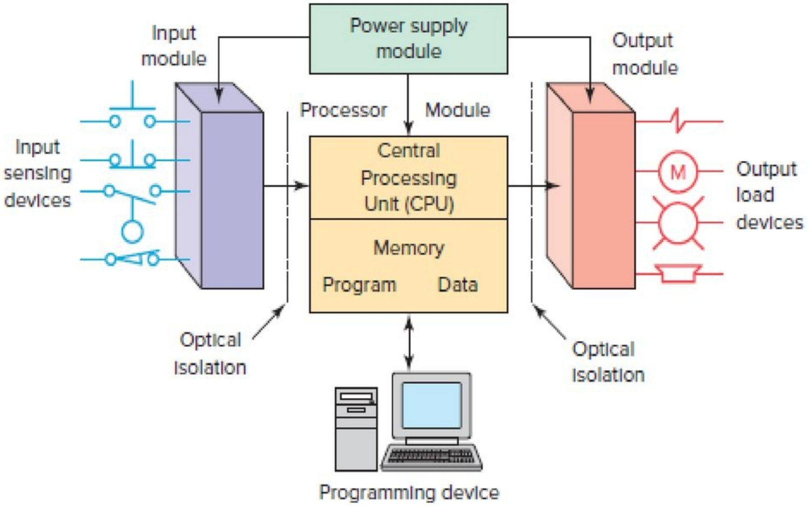


Programmable Logic Controller (PLC)

- **Main parts**
  - Power supply
  - I/O modules
  - Central Processing Unit (CPU)
  - Memory
- **Working Process**
  - Scan cycle
    - Read inputs
    - Execute the program
    - Write outputs
- **Main Features**
  - Flexible
  - Ease of use
  - Reliable, intended-for and therefore tolerant-of more severe conditions (e.g., dust, moisture, heat, cold)

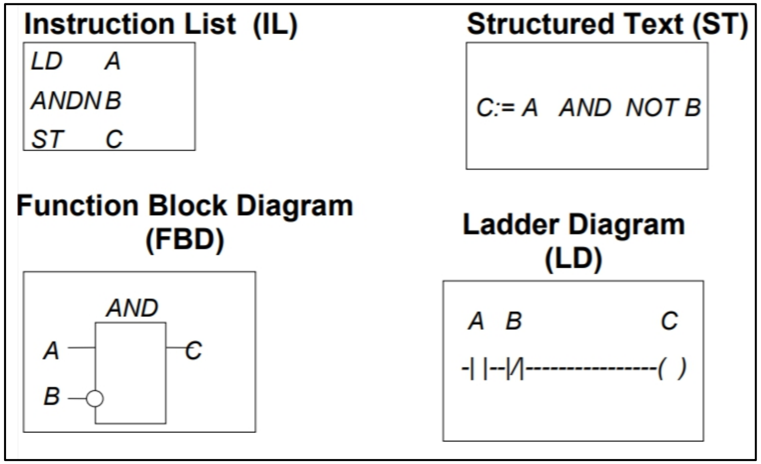


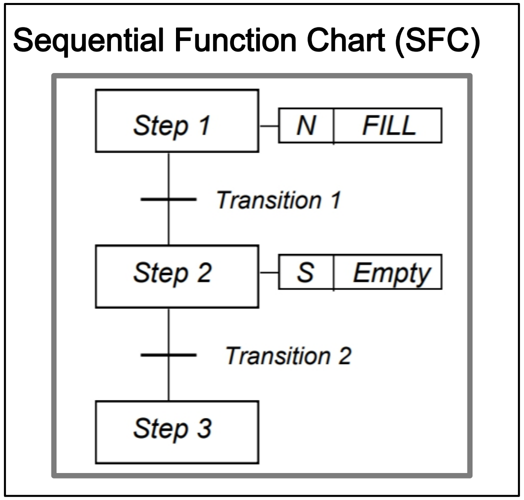
PLC Architecture



Programmable Logic Controller (PLC)

- **Programming** (IEC 61131-3)
  - Instruction List (IL)
  - Structured Text (ST)
  - Ladder diagram
    - widely used
    - most popular language for PLC
    - based on the graphical presentation of Relay Ladder Logic
  - Function Block Diagram (FBD)
  - Sequential Function Chart (SFC)
    - use to structure the internal organization of a program and function blocks

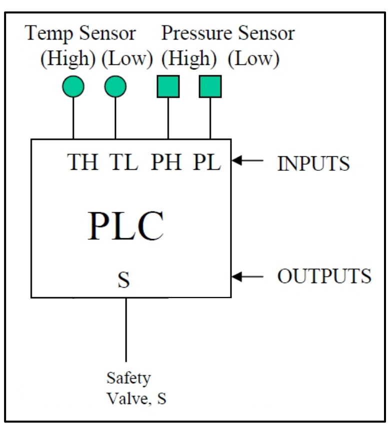


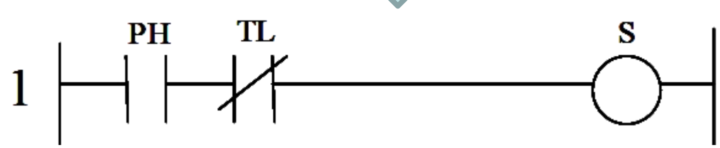


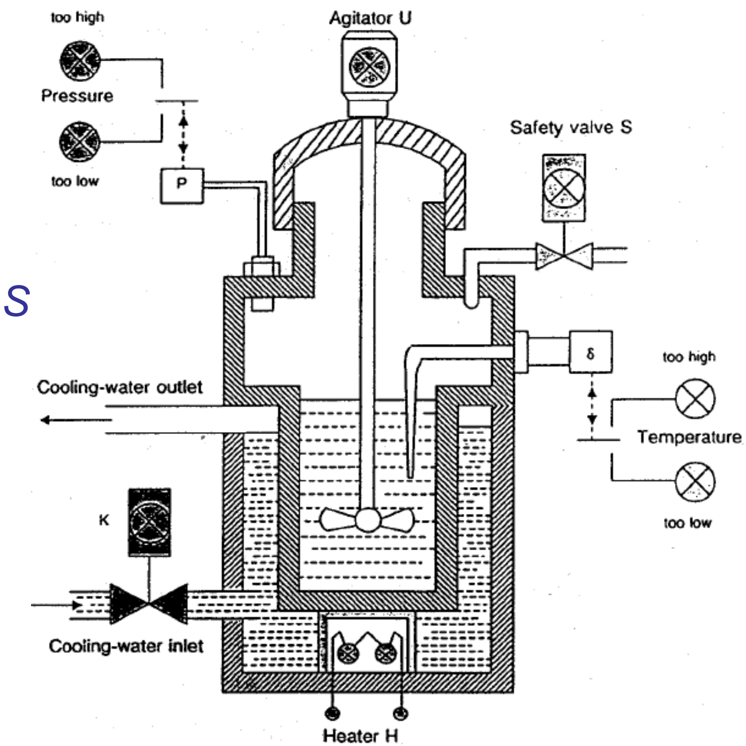
Programmable Logic Controller (PLC)

- **Programming - Example**
  - Reactor Vessel Exercise
    - Safety valve S is activated when
      - *pressure P is too high and*
      - *temperature δ is too high or normal*

IF *PH is ON* **AND** *TL is OFF* **THEN** *turns on S*



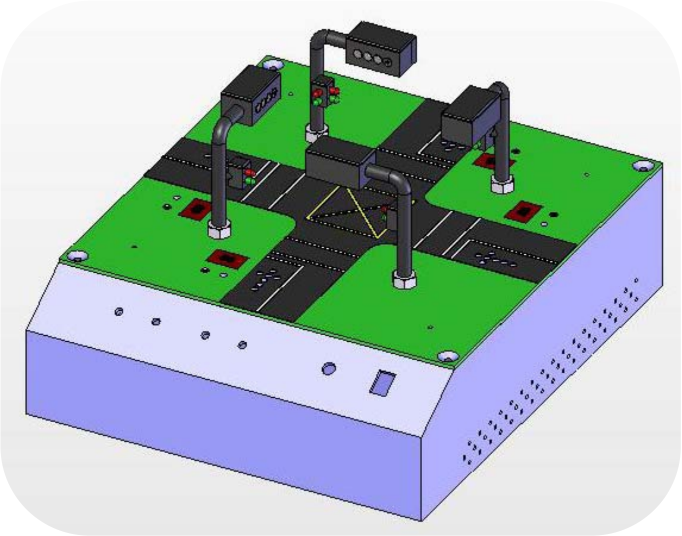


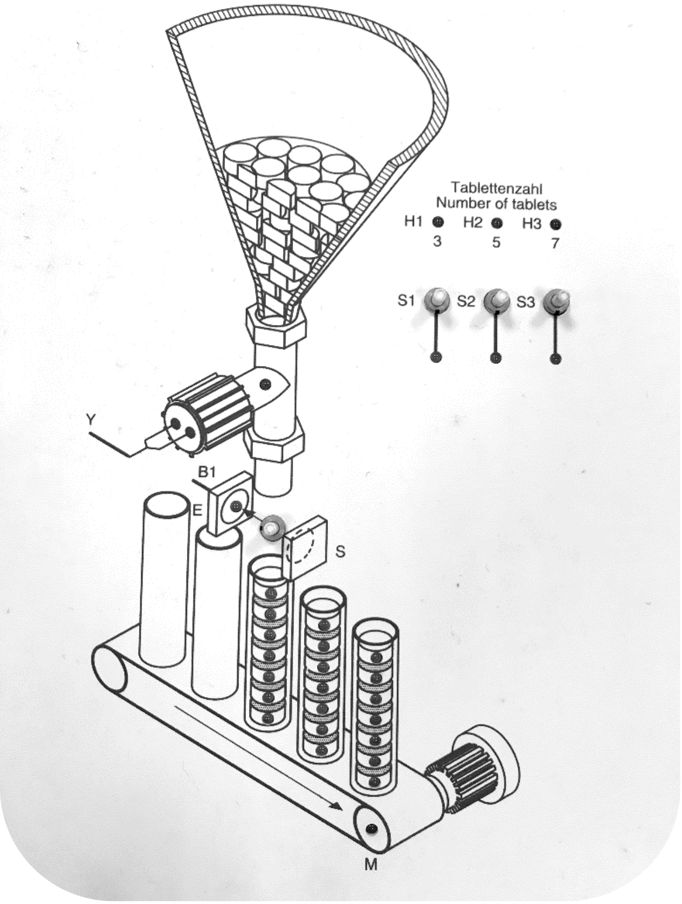


Process Schematic of Reaction Vessel

Programmable Logic Controller (PLC)

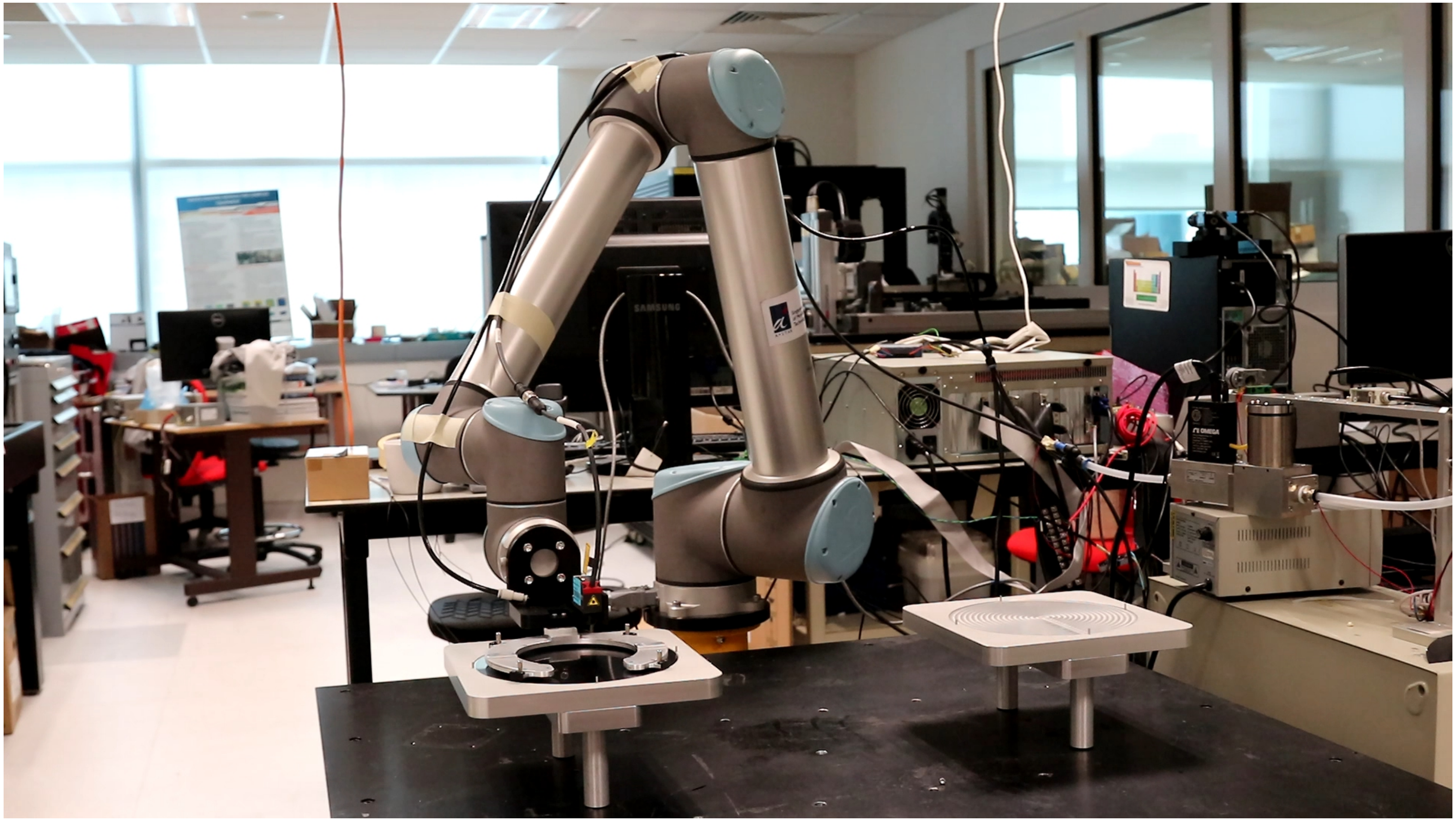
- **Applications**
  - Industrial automation
  - Traffic light
  - Elevator
  - …





Robot Operating System (ROS)

- Industrial Robot for Thin-wafer Handling - demo video



Robot Operating System (ROS)

- **About**
  - The **Robot Operating System (ROS)** is a flexible framework for writing robot software
  - It is a collection of tools, libraries, and conventions that aim to simplify the task of creating complex and robust robot behavior across a wide variety of robotic platforms
  - ROS was built from the ground up to encourage **collaborative** robotics software development

(Source: https://www.ros.org/)

Robot Operating System (ROS)

- **ROS Applications – video**
  - A montage showing the variety of robots in the ROS community

thank you
danke
謝謝
ngiyabonga
teşekkür ederim
рахмат
Баярлалаа
спасибо
mersi
kia ora
barka
welalin
tack
spas
mahalo
tapadh leat
faafetai lava
vinaka
blagodaram
спасибі
dank je
misaotra
matondo
paldies
grazzi
gracias
хвала
asante
manana
obrigada
tenki
murakoze
chokrane
kiitos
dankie
nanni
nandri
dhanyavad
mauruuru
hvala
gràçie
bayarlalaa
köszönöm
bedankt
enkosi
dziękuję
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gratias ago
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ありがとう
tanemirt
grazie
kam sah hamnida
rahmat
terima kasih
rahmet
ευχαριστώ
diolch
dhanyavadagalu
shukriya
mercê
мерси
তোমাকে ধন্যবাদ
감사합니다
xièxie
merci

Assessment

- **Please check the "CAs (EE5111/5061)" folder in LumiNUS**
  - The second part (CA3b) of my assignment will be uploaded on next Friday (Oct. 8, 2021)
- **Submission Method**
  - Soft copy (Word or .pdf)
- **Submission deadline:**
  - Friday (Nov. 19, 2021) of the reading week

Assessment

- CA3b sample

EE5111/5061 Selected Topics in Industrial Control & Instrumentation

CA3b Assignment for Control Design

(Academic Year 2021/22, Semester I)

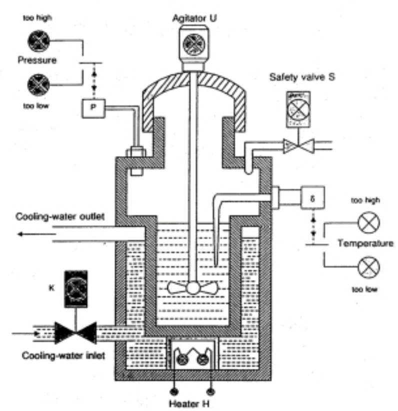
This assignment will contribute 20% to the total marks for the module EE5111 and 10% for EE5061.
Please make sure your CA3b report is clear and readable.
Please submit your CA3b report (soft copy: Word or .pdf) into the "CA3b - Submission" folder in LumiNUS.
Submission deadline: **Nov. 19, 2021**
Important: Each submitted CA3b report must be an individual report.

1. Consider a second-order system shown in the following transfer function, please study this second-order system and design the PID controller for the system.

$$G(s) = \frac{1}{s^2 + 12s + 3}$$

(1) Find a state-space model for the above system.
(2) Design a PID controller for the system using the LQR technique, simulate the designed control system and show the step responses of the designed control system.
(3) Discuss the effects of weightings Q and R on system performance and monitor the control signal.
(**Note:** Any programming language such as MATLAB, Simulink, Python, C++, etc. can be used for the simulations. In MATLAB, the function "lqr" can help to design the controller parameters via LQR.)

2. Consider a reactor vessel which process schematic is shown in the following figure, a chemical process is to take place in this reaction vessel at a specific temperature and at a specific pressure.



The reaction vessel has a thermal detector for measuring the temperature and a pressure gauge for the pressure.

1 of 2

A+

Study Hard!

Good Luck!