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Adaptive robust control of soft bending actuators: an empirical nonlinear model-based approach

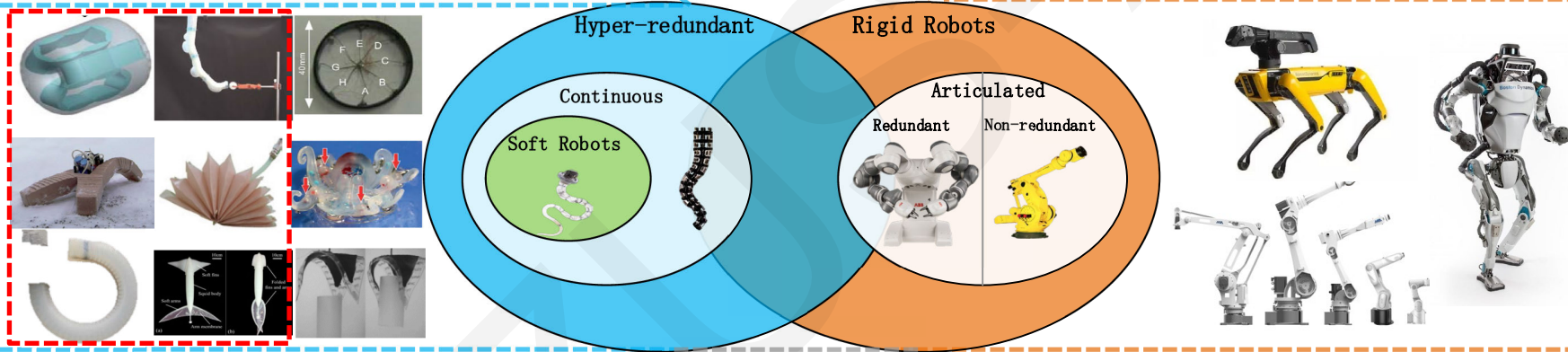
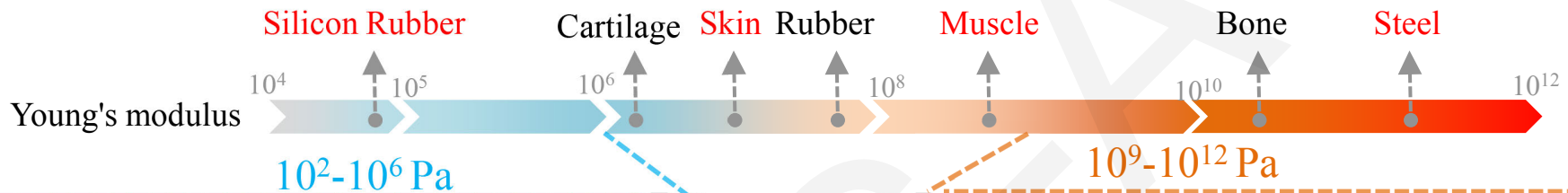
Key Words:

Pneumatic soft bending actuator, Empirical nonlinear model identification, Unbalanced pneumatic proportional valve modeling, Adaptive robust control, Trajectory tracking



BACKGROUND

Soft Robotics

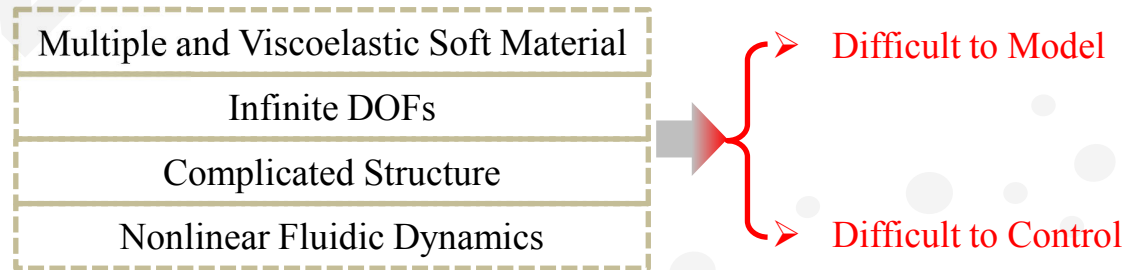


Fluidic Soft Robotics

Advantages

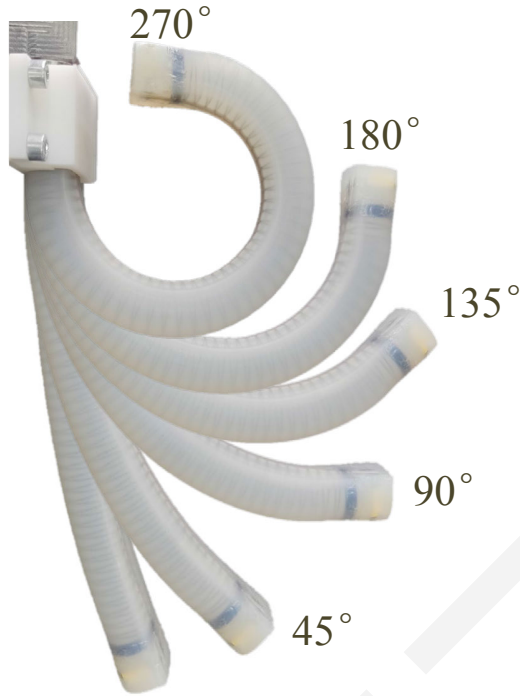
- High Compliance
- Excellent deformability and output force
- High power-to-weight ratio
- Low manufacturing cost

Disadvantages



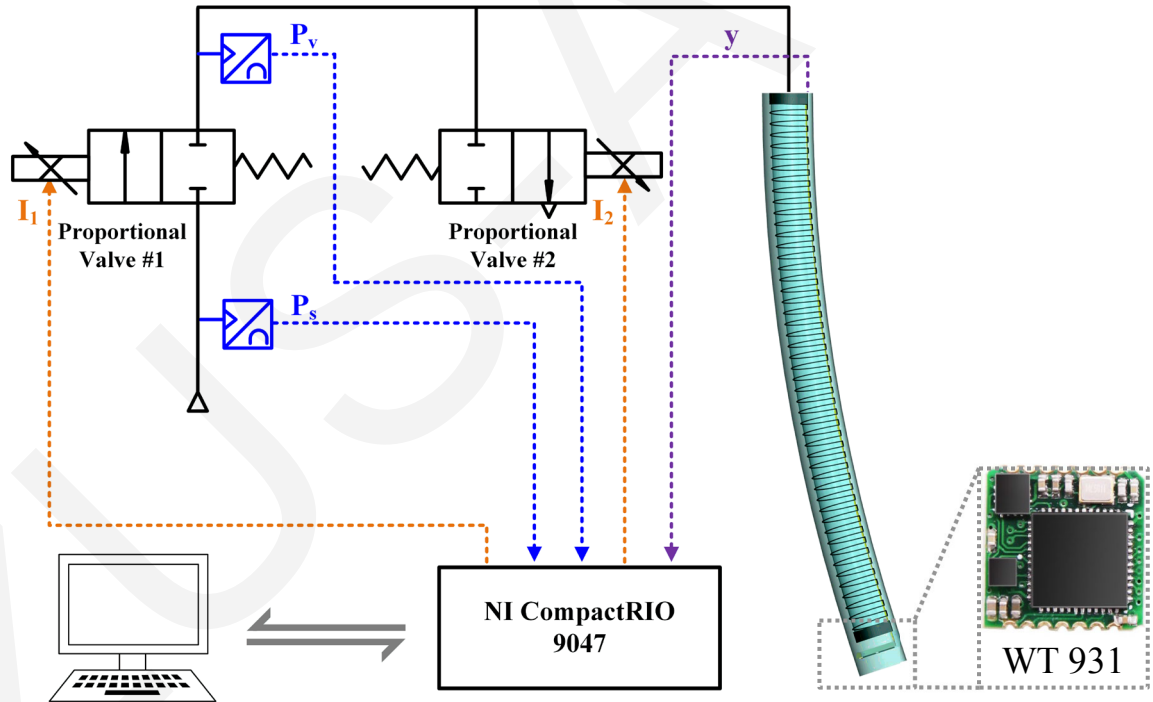
Method: System Schematic

Soft Bending Actuator

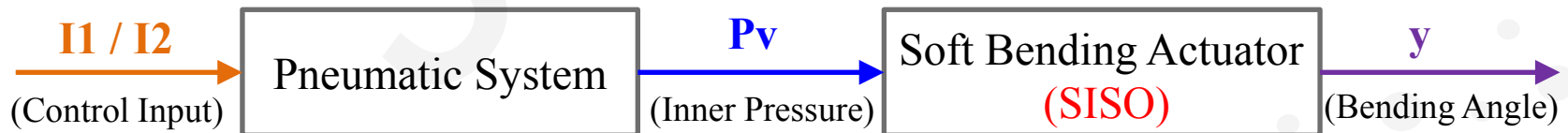


Initial Position: 18°

System Schematic



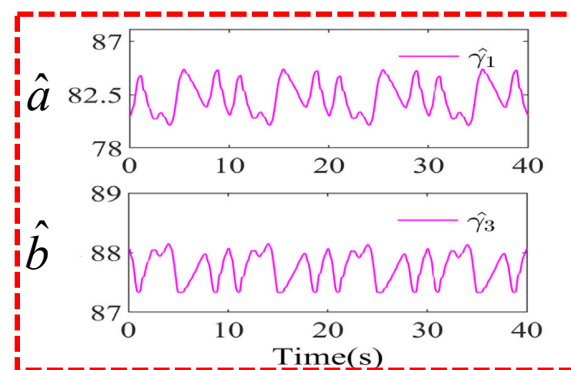
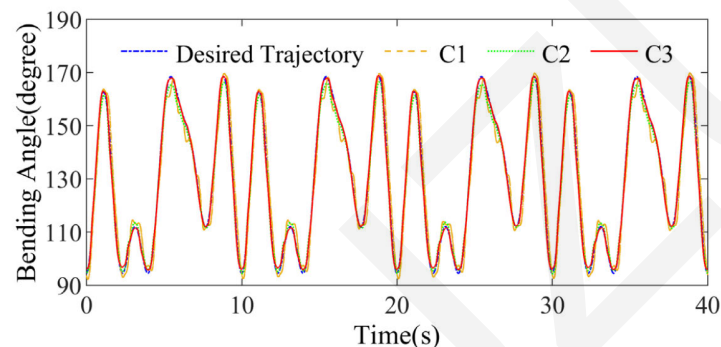
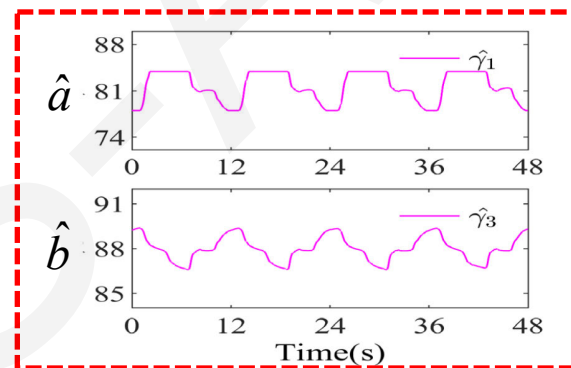
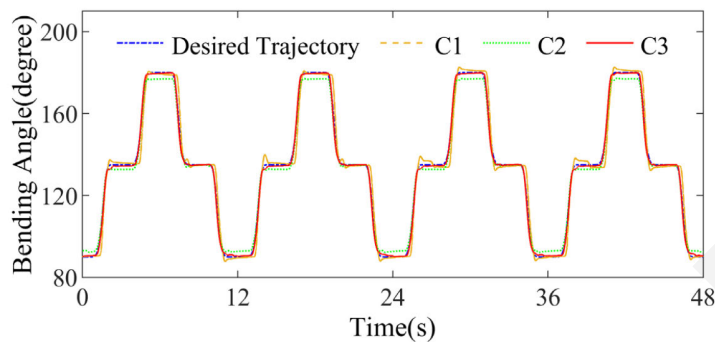
System Structure



Method: Conventional Model of Soft Bending Actuator

□ Conventional Linear Model: $\ddot{y}(t) + c\dot{y}(t) + ay(t) = bP_v$

□ Trajectory Tracking and Parameter Adaptation



- ◆ Our previous work was published in IEEE Robotics and Automation Letters:
Chen C, Tang W, Hu Y, et al. Fiber-Reinforced Soft Bending Actuator Control Utilizing On/Off Valves[J]. IEEE Robotics and Automation Letters, 2020, 5(4): 6732-6739.
- ◆ In our previous work, the parameters of linear model are found to vary with bending angle.

Method: Empirical Nonlinear model of Soft Bending Actuator

Empirical Nonlinear Model

◆ Model Structure: $\ddot{y}(t) + c(y)\dot{y}(t) + a(y)y(t) = b(y)P_v + d + \Delta_1$

◆ Parameters Expansion: $a(y) = \sum_{i=0}^m a_i y^i(t)$; $b(y) = \sum_{j=0}^n b_j y^j(t)$; $c(y) = \sum_{k=0}^r c_k y^k(t)$

Stable Filter

$$H_f(s) = \frac{1}{(\tau_f s + 1)^n}$$

Empirical Nonlinear Model Identification

◆ Regression Model:

$$Y = \Phi^T \theta_{SBA}$$

$$\begin{cases} Y = \ddot{y}_f \end{cases}$$

$$\begin{cases} \Phi = [(-y)_f, \dots, (-y^{m+1})_f, (y^0 P_v)_f, \dots, (y^n P_v)_f, (-y^0 \dot{y})_f, \dots, (-y^l \dot{y})_f, (1)_f]^T \end{cases}$$

$$\begin{cases} \theta_{SBA} = [a_0, \dots, a_m, b_0, \dots, b_n, c_0, \dots, c_l, d]^T \end{cases}$$

◆ LSE Parameter Estimation:

➤ Nominal Values: $\hat{\theta}_{SBA} = [\Phi \Phi^T]^{-1} \Phi Y$

➤ Standard Deviation: $\hat{\sigma} = \text{Diag} \left[\sqrt{[\Phi \Phi^T]^{-1} \frac{\text{Sum} \left((Y - \Phi^T \hat{\theta}_{SBA})^2 \right)}{L - (m + n + r + 4)}} \right]$

Bounded Parameters

$$\theta_{SBA} \in \hat{\theta}_{SBA} \pm \beta_0 \hat{\sigma}$$

Method: Pneumatic System

Inner Pressure Dynamics

◆ Assumption: Inner pressure dynamics were regarded as an Isothermal Process

◆ From the Ideal Gas Law:

$$\dot{P}_v = \frac{RT}{S_p V} (Q_{m1} - Q_{m2} - Q_{ml}) + \Delta_2$$

Inner Pressure
Chamber Volume
Charging Mass Flow Rate
Exhaust Mass Flow Rate

← Unmodeled Uncertainties
Leakage Mass Flow Rate

Unbalanced Pneumatic Proportional Valve Model

◆ Valve Spool Dynamics:

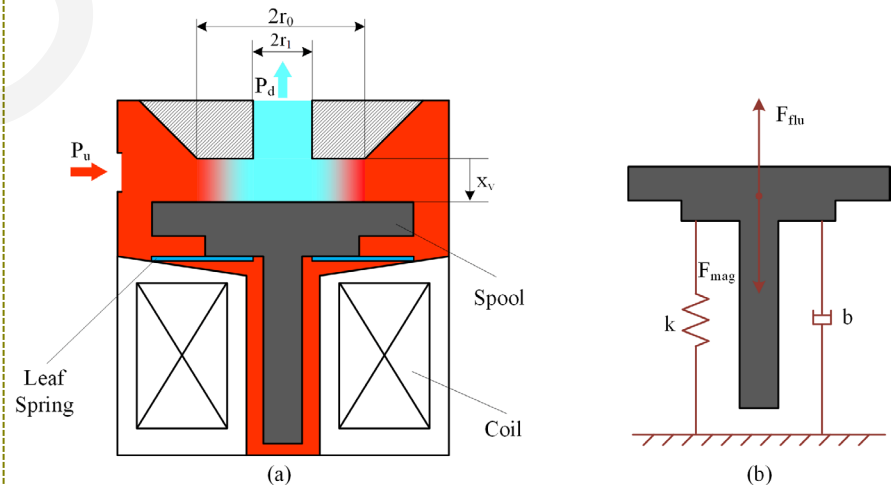
$$F_{mag} = m\ddot{x}_v + b\dot{x}_v + kx_v + F_{flu} + F_0$$

◆ Unbalanced Steady Airflow Force

$$F_{flu} = \left(k_{f1} - k_{f2} \frac{x_v}{x_{vmax}} \right) \pi (P_u r_0^2 - P_d r_1^2)$$

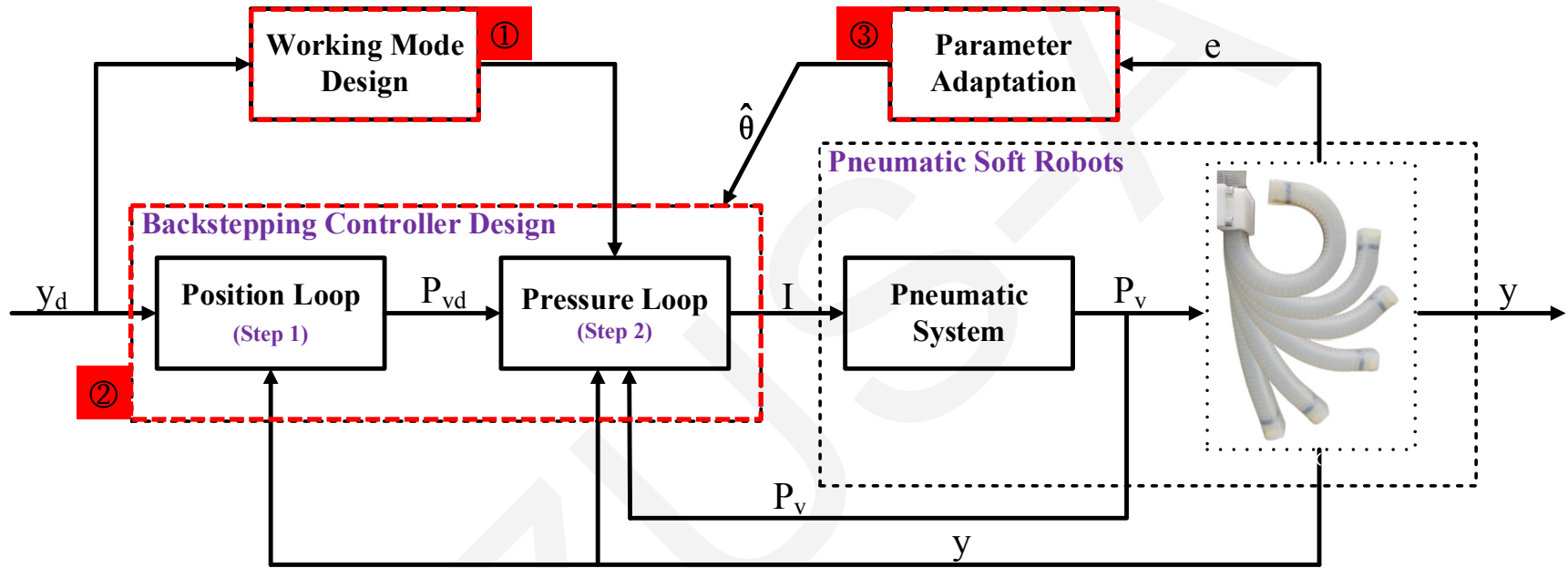
◆ Assumption: Valve Dynamics were Neglectable

$$A_v = 2\pi r_1 x_v = \frac{k_{v1}I - k_{v3}P_u + k_{v5}P_d - k_{v6}}{1 - k_{v2}P_u + k_{v4}P_d}$$



Method: Adaptive Robust Controller

Controller Structure:



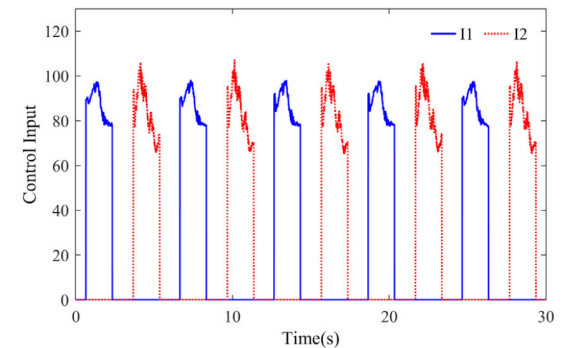
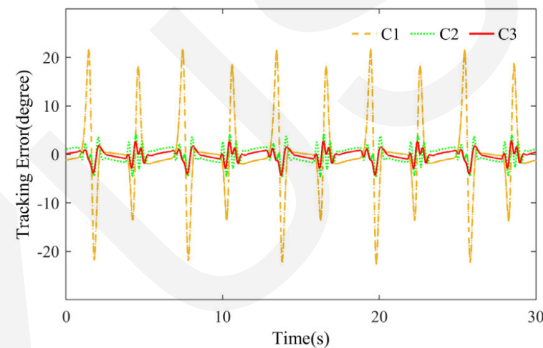
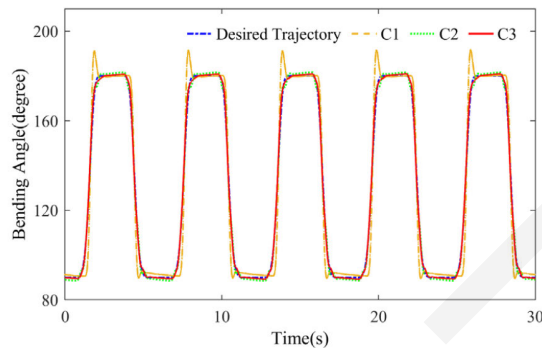
- ◆ The Working Mode was used to separate the air charging and exhaust processes.
- ◆ The Backstepping Robust Controller was used to govern the nonlinear and uncertain system with a guaranteed trajectory tracking performance.
- ◆ The discontinuous projection based Parameter Adaptation was introduced to update the model parameters and further improve the controller performance.

Results: Trajectory Tracking Control

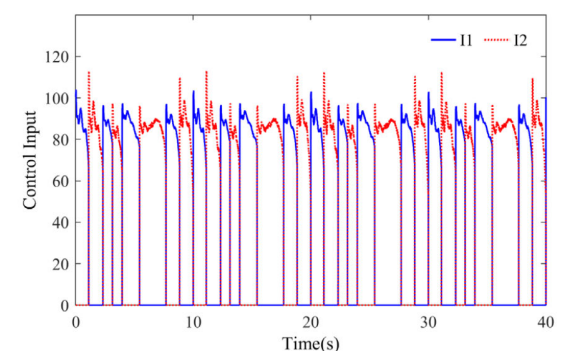
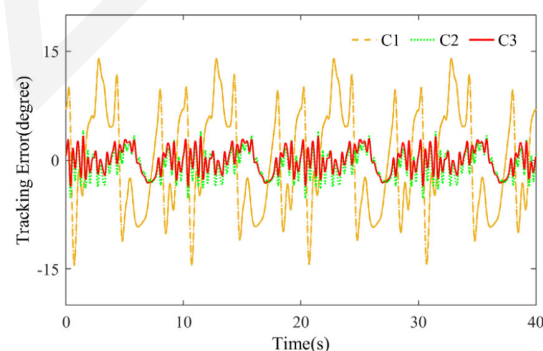
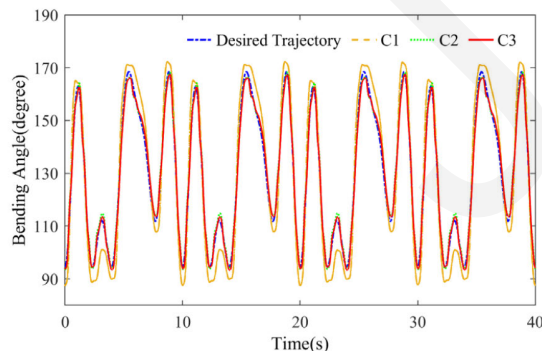
□ Comparative Experiments

- C1: PID + Velocity and Acceleration Feedforward (PID+FF)
- C2: Sliding Mode Controller (SMC)
- C3: Adaptive Robust Controller (ARC)

◆ T1 Trajectory Tracking



◆ T2 Trajectory Tracking



CONCLUSION

- Improved Model Structure:
 - ◆ The Empirical Nonlinear Model was identified to describe the nonlinear behavior of Pneumatic Soft Bending Actuator.
 - ◆ A modified valve flow rate model was developed to accurately describe the mass flow rate of the unbalanced pneumatic proportional valve.
- Backstepping Controller Design: The Adaptive Robust Controller was designed to deal with the nonlinear and uncertain system with guaranteed performance.
- Experimental Validation: The trajectory tracking experiments demonstrated the effectiveness of the Empirical Nonlinear Model and the proposed Adaptive Robust Controller.



Thank You!

