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Integral Sliding Mode Backstepping Control of an Asymmetric Electro-Hydrostatic Actuator Based on Extended State Observer

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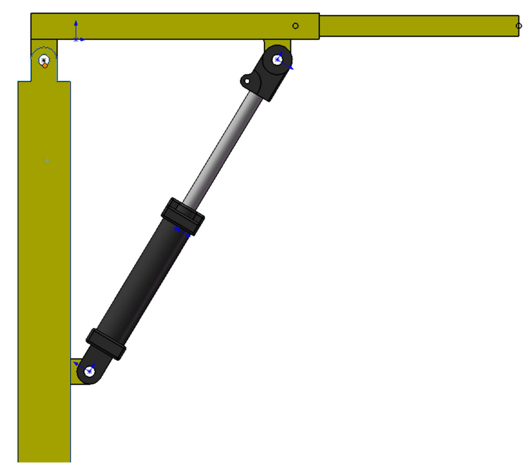

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1.1 Background

1. Unbalanced flow:

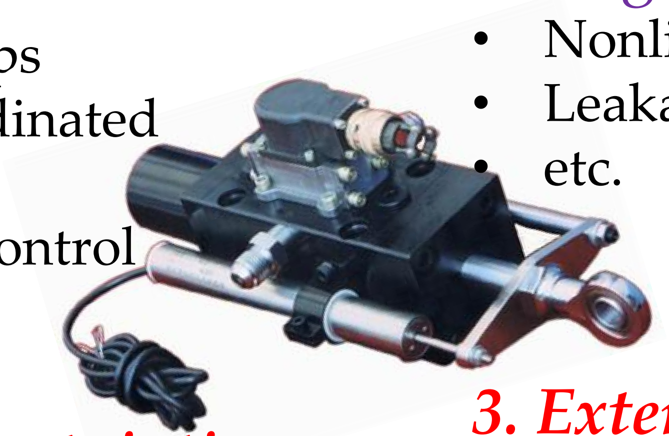
Unequal effective cross-section areas

- Asymmetric pumps
- Pump-valve-coordinated
- Dual-pumps
- Robust adaptive control
- MPC control
- etc.

2. Nonlinearities:

Nonlinear friction and leakages

- Nonlinear friction model
- Leakage model
- etc.



3. External disturbances:

Unmodeled friction force and load force

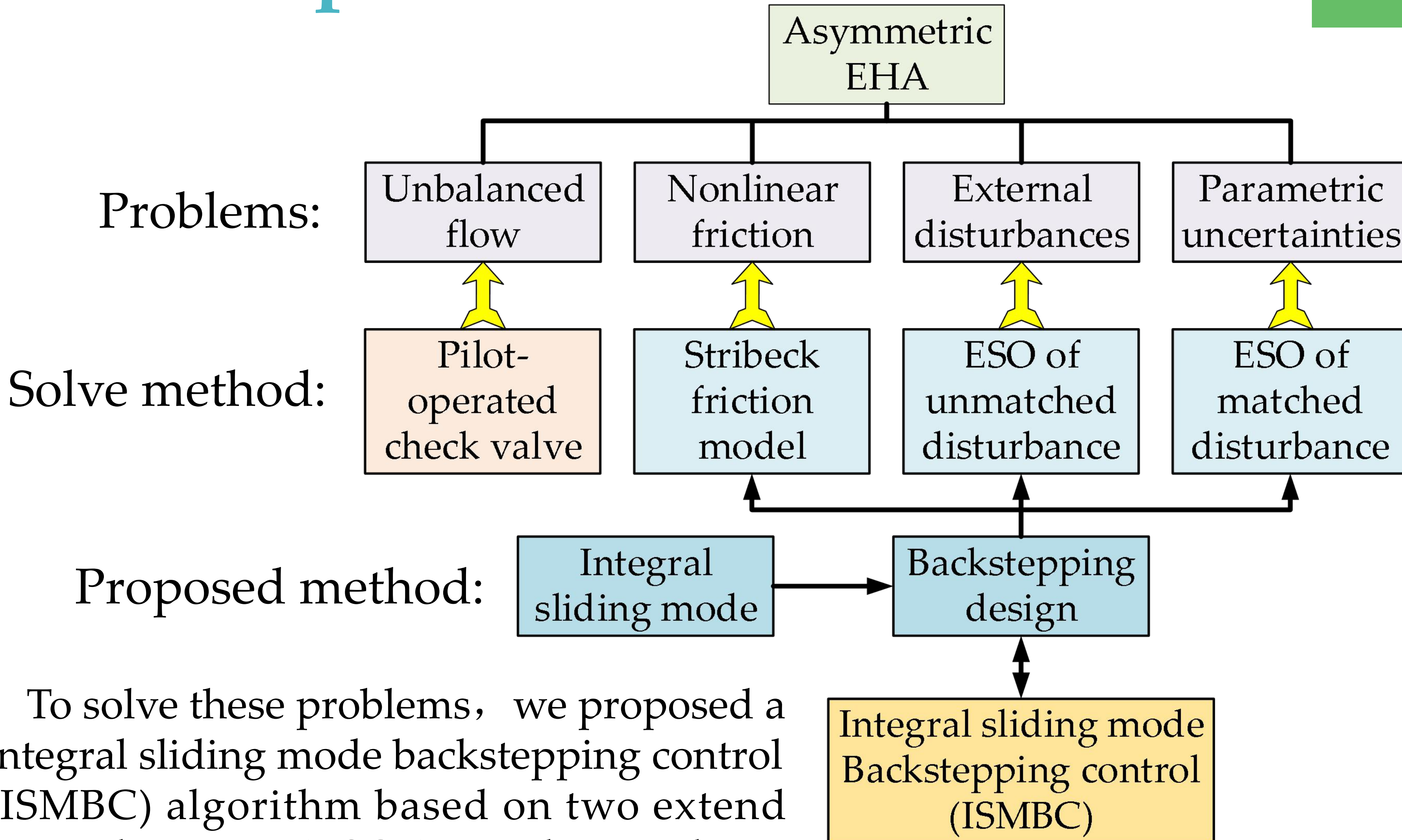
- Extended disturbance observer
- Nonlinear disturbance observer
- etc.

4. Parametric uncertainties:

Model inaccuracy and parameters variation

- High control gain
- Neural networks
- Extended state observer
- etc.

1.2 Proposed method



To solve these problems, we proposed a integral sliding mode backstepping control (ISMBC) algorithm based on two extend state observers (ESOs). As shown above structure diagram.

1.3 Introduction to the EHA

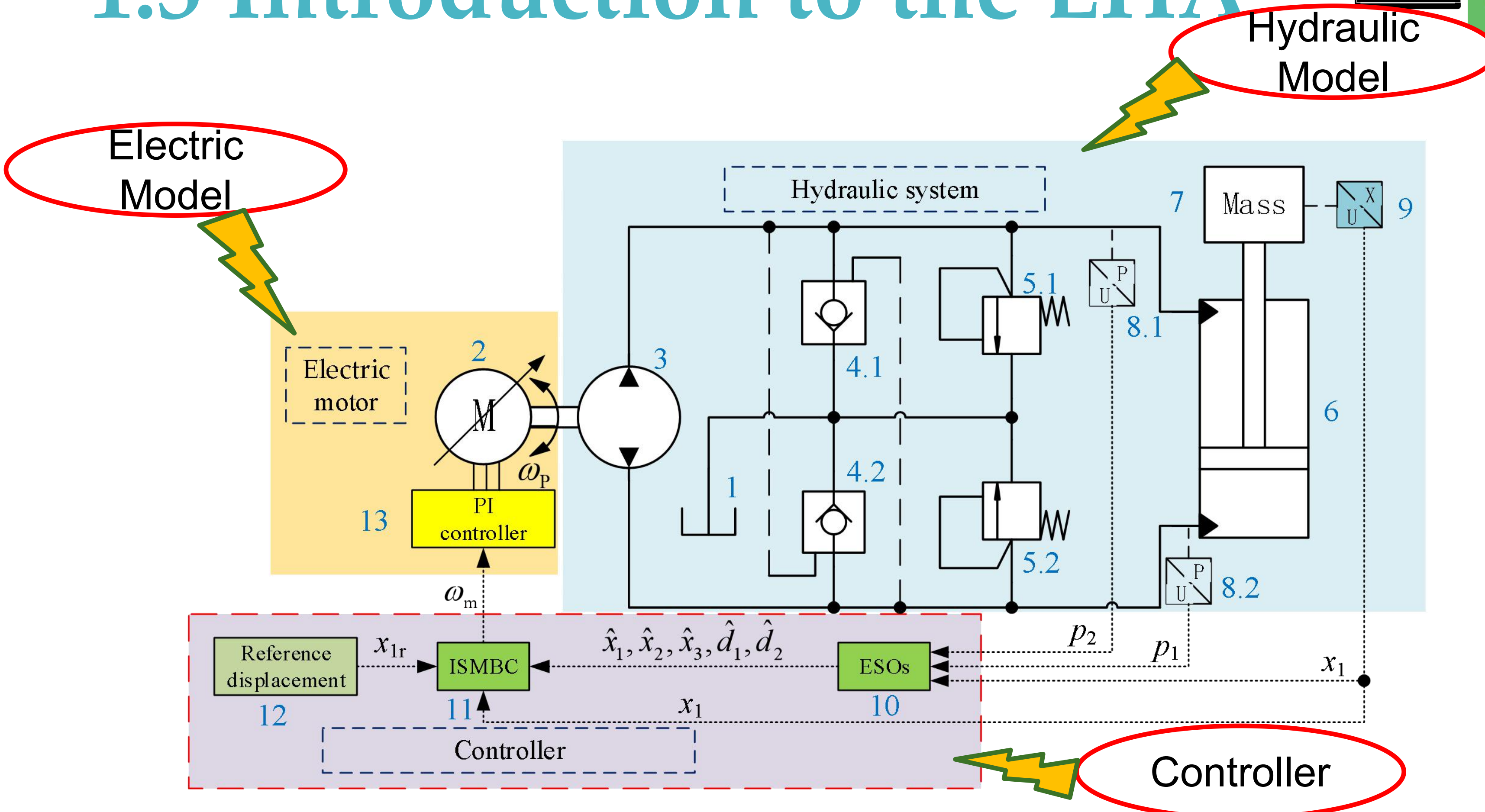


Figure 1: Schematic diagram of an asymmetric EHA

1: tank. 2: servo motor. 3: bidirectional pump. 4: pilot-operated check valve. 5: relief valve. 6: asymmetric hydraulic cylinder. 7: mass of boom and load. 8: pressure sensor. 9: displacement sensor.

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2.1 Load force analysis

The micro-crane is used as a test platform, which can provide a variable load force, by changing the load mass. Based on Newton's second law, the output force equation of the EHA can be given by:

$$F_{\mathrm{Cyl}} = \frac{\left[J\dfrac{d^2\theta}{dt^2} + mgr_m \sin(\theta_m) + m_l g r_l \sin(\theta_l) \right]}{d_1 \sin(\alpha)} \quad (1)$$

where F_{Cyl} is the output force of cylinder; g is gravitational acceleration; J is the rotational inertia of boom; $(d^2\theta)/dt^2$ is the angular acceleration; and the other symbols are shown in Figure 2.

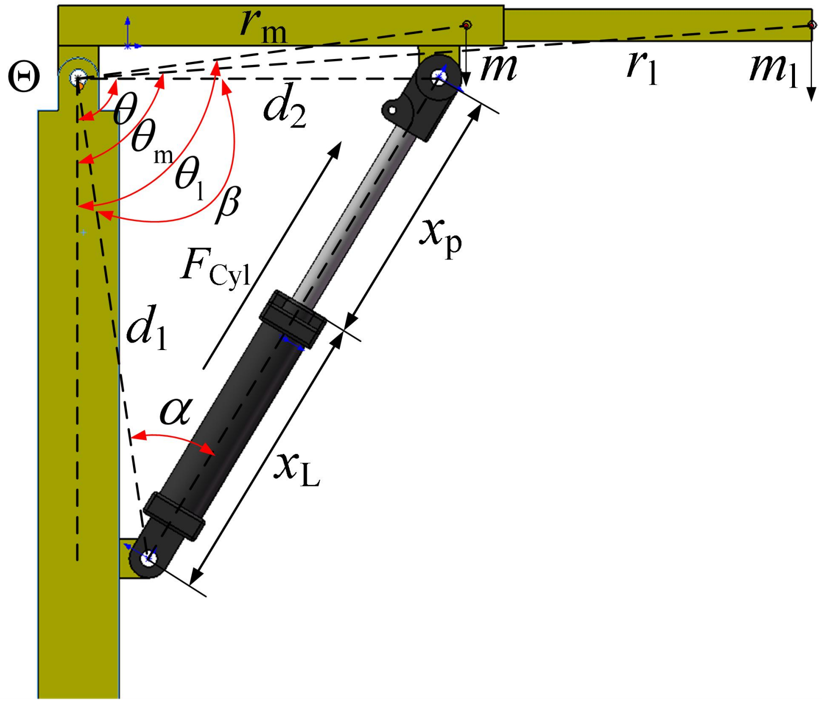

Figure 2. Structure diagram of the micro-crane.

2.2 Principle analysis of EHA

The EHA, installed on the micro-crane as shown in Figure 2, runs in two operating conditions including extending and retracting with positive load, as shown in Figure 3.

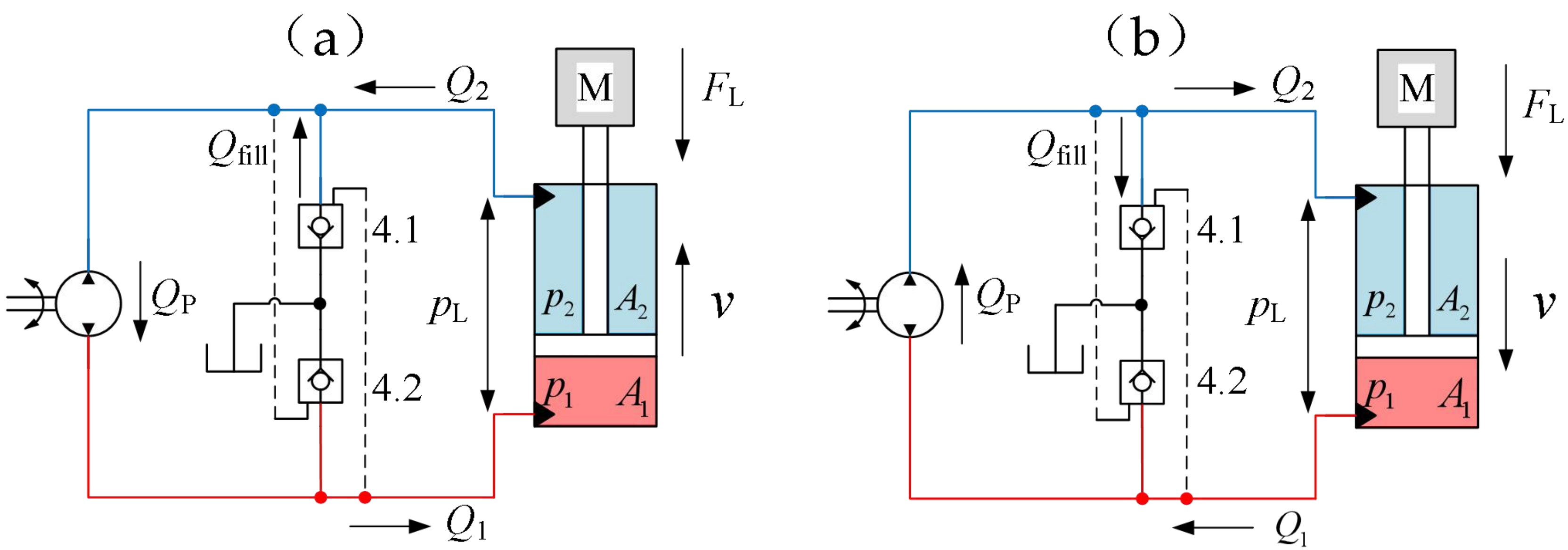

Figure 3. Schematic diagram of two operating conditions of EHA: (a) the EHA resistive extension; (b) the EHA assistive retraction

2.3 Modeling

1) Electric Motor Model

Electric motor is regarded as a first-order system, and PI is adopted to control its speed. The electric motor control flow diagram is shown in Figure 4.

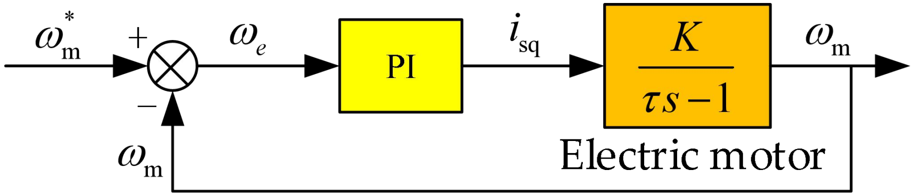

Figure 4. The control flow diagram of the electric motor

2) Friction Model of Cylinder

Stribeck friction model be used to identify nonlinear friction force, the model can be given by

$$\begin{cases} F_f(\dot{x}_P) = (F_C + (F_{brk} - F_C)e^{(-c_v|v|)})\text{sgn}(v) + fv, |v| > v_{th} \\ F_f(\dot{x}_P) = v\dfrac{\left(fv_{th} + \left(F_C + \left(F_{brk} - F_C\right) \cdot e^{\left(-c_v|v|\right)}\right)\right)}{v_{th}}, |v| < v_{th} \end{cases} \quad (2)$$

2.3 Modeling

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3）System Model of the EHA

Defining state variables $x=[x_1, x_2, x_3]=[x_\mathrm{P}, \dot{x}_\mathrm{P}, p_\mathrm{L}]$ the state-space equation of the EHA can be written as:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = \theta_1 x_3 - \theta_2 F_\mathrm{f}(x_2) - \theta_2 F_\mathrm{L} - \theta_2 d_\mathrm{t} \\ \dot{x}_3 = b u_\omega - \theta_3 x_2 - \theta_4 x_3 \\ y = x_1 \end{cases} \tag{3}$$

Unmatched disturbance $d_1(t) = -\theta_2 F_\mathrm{L} - \theta_2 d_\mathrm{t}$ $\quad$ $d_2(t) = \Delta b u_\omega - \Delta\theta_3 x_2 - \Delta\theta_4 x_3$ Matched disturbance

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = \theta_1 x_3 - \theta_2 F_\mathrm{f}(x_2) + d_1(t) \\ \dot{x}_3 = b u_\omega - \theta_3 x_2 - \theta_4 x_3 + d_2(t) \\ y = x_1 \end{cases} \tag{4}$$

where $\theta_1 = \dfrac{A_1}{m},\ \theta_2 = \dfrac{1}{m},\ \theta_3 = \dfrac{2\kappa\beta_\mathrm{e} A_1}{V_\mathrm{t}},\ \theta_4 = \dfrac{2\kappa\beta_\mathrm{e} c_\mathrm{i}}{V_\mathrm{t}},\ b = \dfrac{\kappa\beta_\mathrm{e} D_\mathrm{P}}{\pi V_\mathrm{t}}.$

2.4 Design of controller

The overall diagram of the proposed **ISMBC** controller is illustrated in Figure 5.

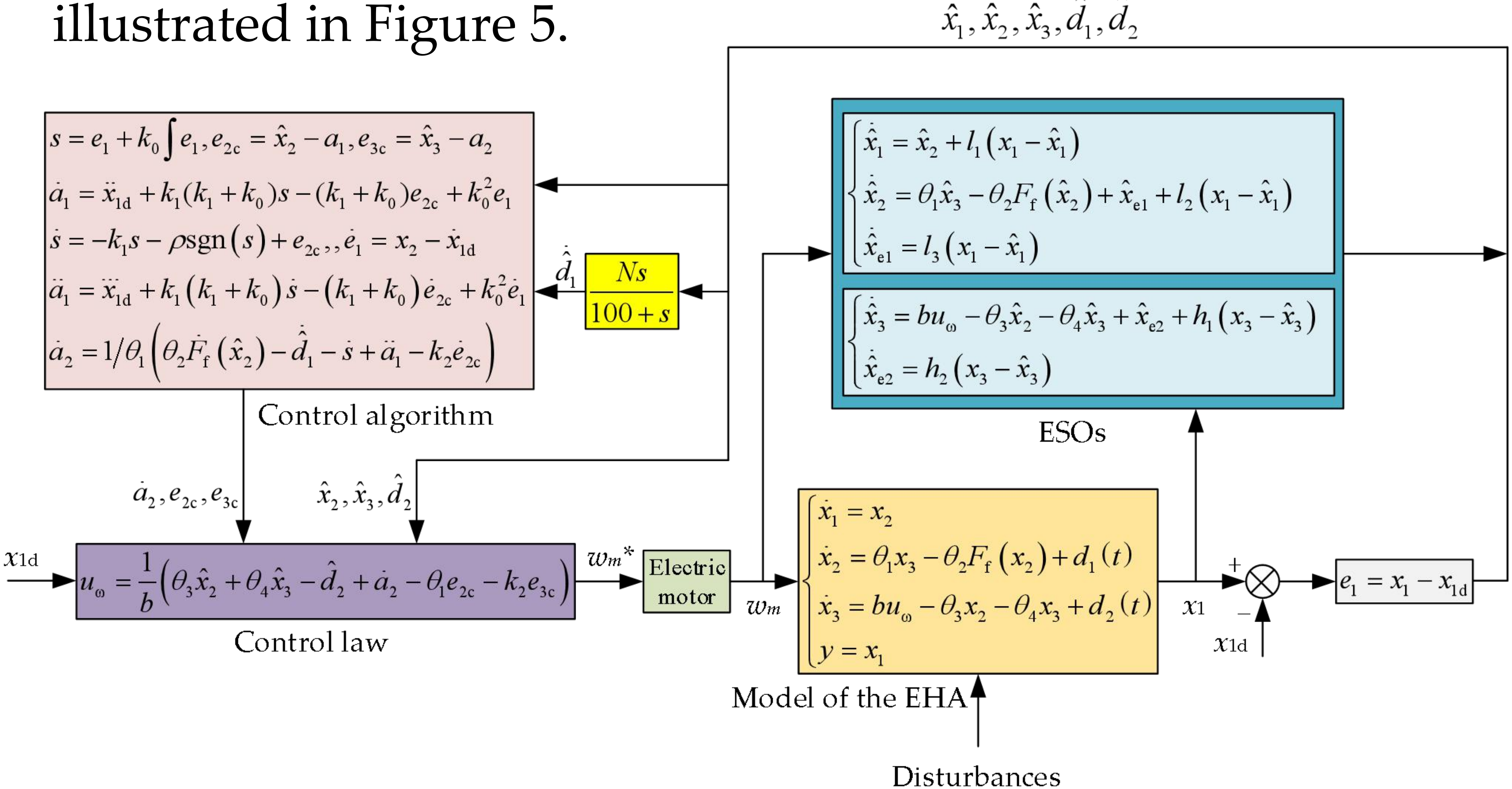

Figure 5. The overall diagram of the control schemes based on two ESOs.

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3.1 Simulation model

A multi-domain model was established in MATLAB/Simulink based on the proposed controller and the designed ESOs, as shown in Figure 6.

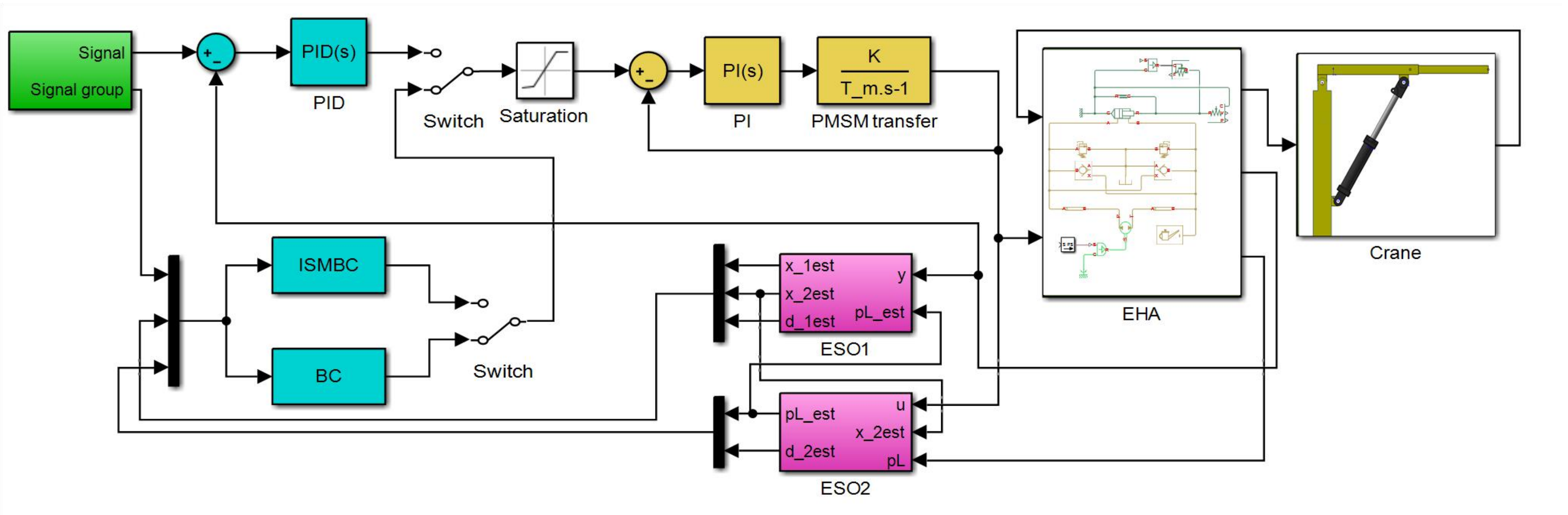

Figure 6. Schematic diagram of multi-domain model

3.2 Observer verification

In view of the fact that the micro-crane mainly performs ascent and descent motions, the controller tracking trajectory was designed as a smooth curve， as shown the curve x_{1d} in Figure 6 (a).

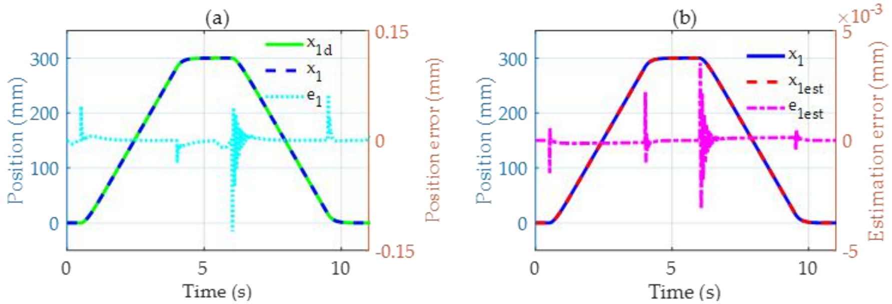

Figure 7. Tracking curve and estimation curve of hydraulic cylinder under ISMBC controller: (a) position tracking and position error; (b) position estimation and position estimation error;

From Figure 7(b) and Figure 8, it can be seen that the designed dual-ESOs can accurate estimate the states and the disturbances.

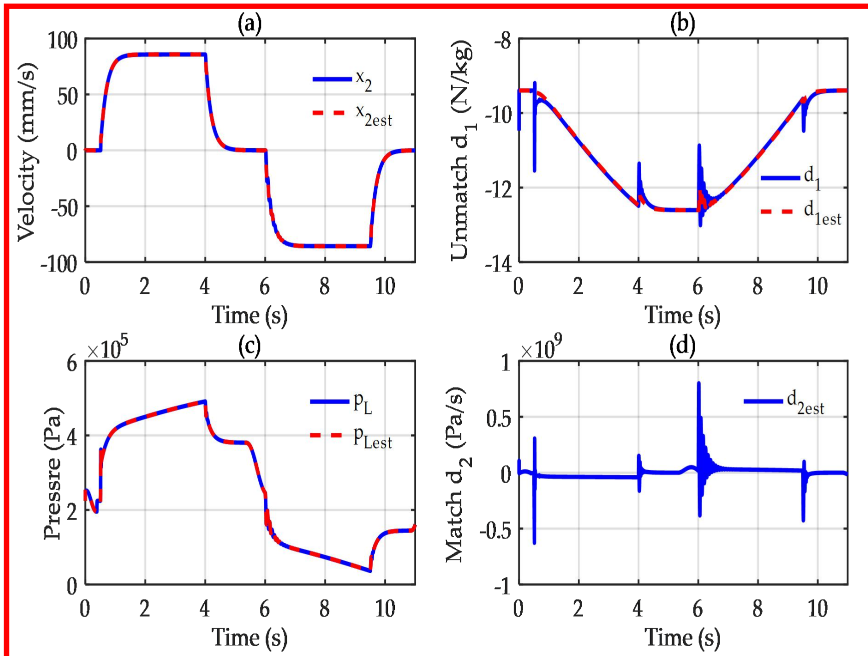

Figure 8. States and disturbances estimation of ESOs under ISMBC controller: (a) velocity estimation; (b) unmatched disturbance estimation; (c) load pressure estimation; (d) matched disturbance estimation.

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3.3 Without load

Without load, the three controllers were used for the closed-loop position control of the EHA.

From Table 3, it can be seen that except for σ_u, the ISMBC controller has the lowest indexes, so its control performance is the best.

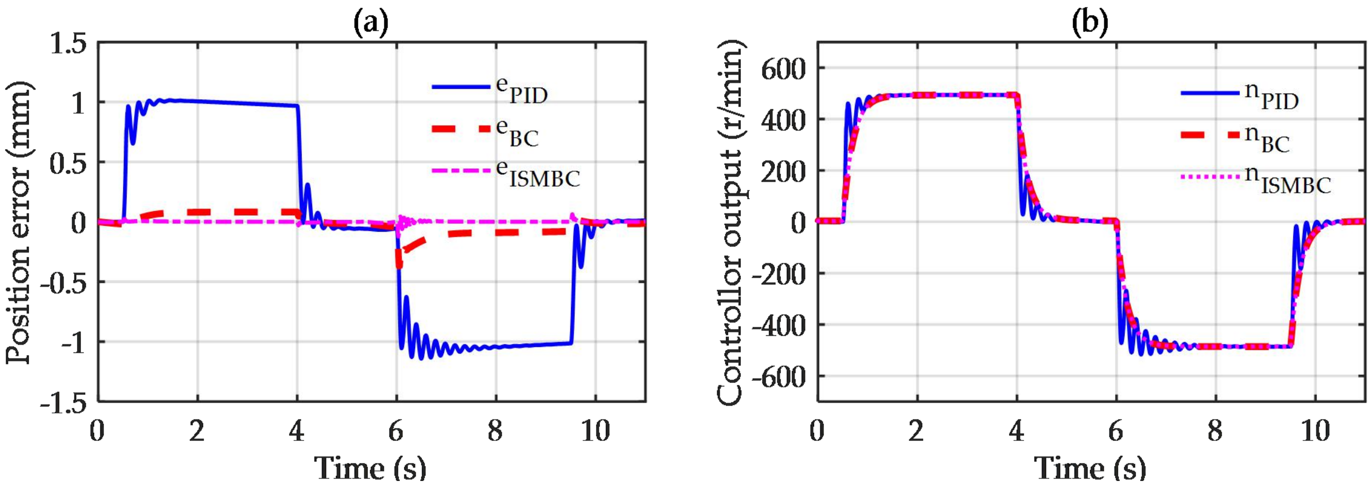


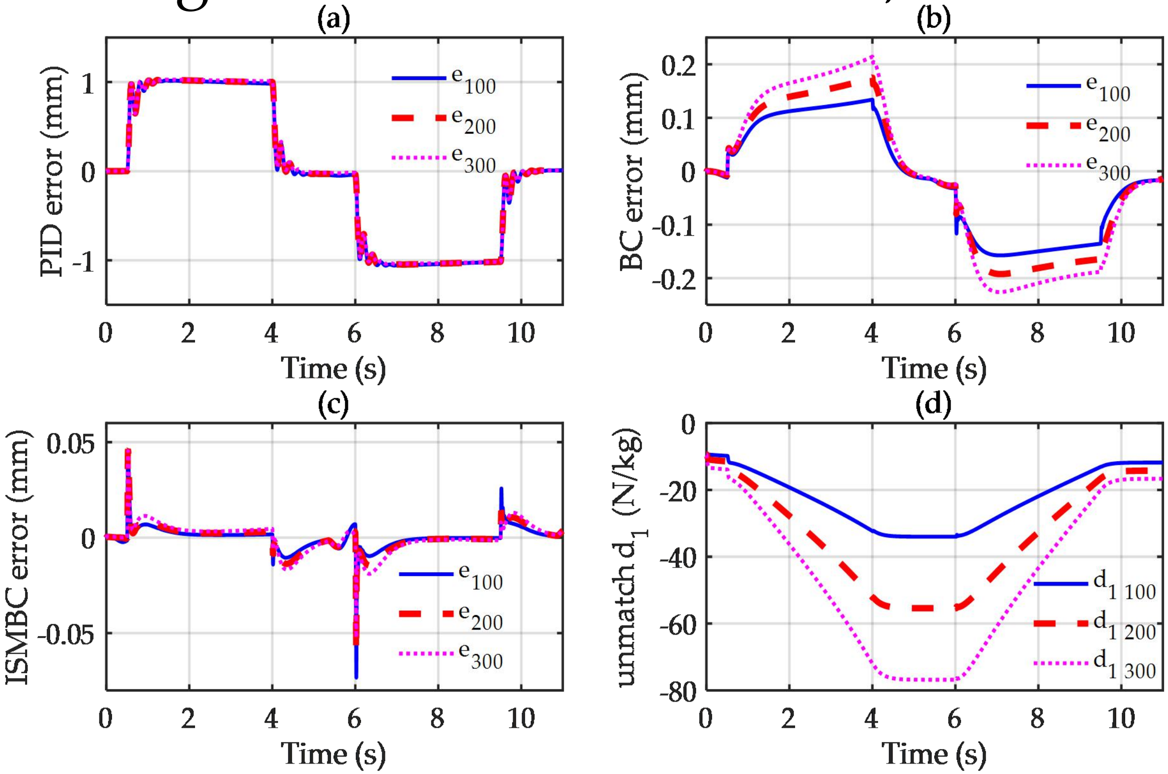
Figure 9. The comparison of control performance of the three controllers without load: (a) position tracking error; (b) controller output.

Table 3. Schematic diagram of multi-domain model

Unit (mm)	M_e	μ_e	σ_e	μ_u	σ_u
PID	1.14	7.17×10^{-2}	0.629	43.28	294.9
BC	0.374	3.11×10^{-2}	9.10×10^{-2}	3.787	272.8
ISMBC	0.124	3.93×10^{-3}	1.92×10^{-2}	1.69	286.9

3.4 With varying loads

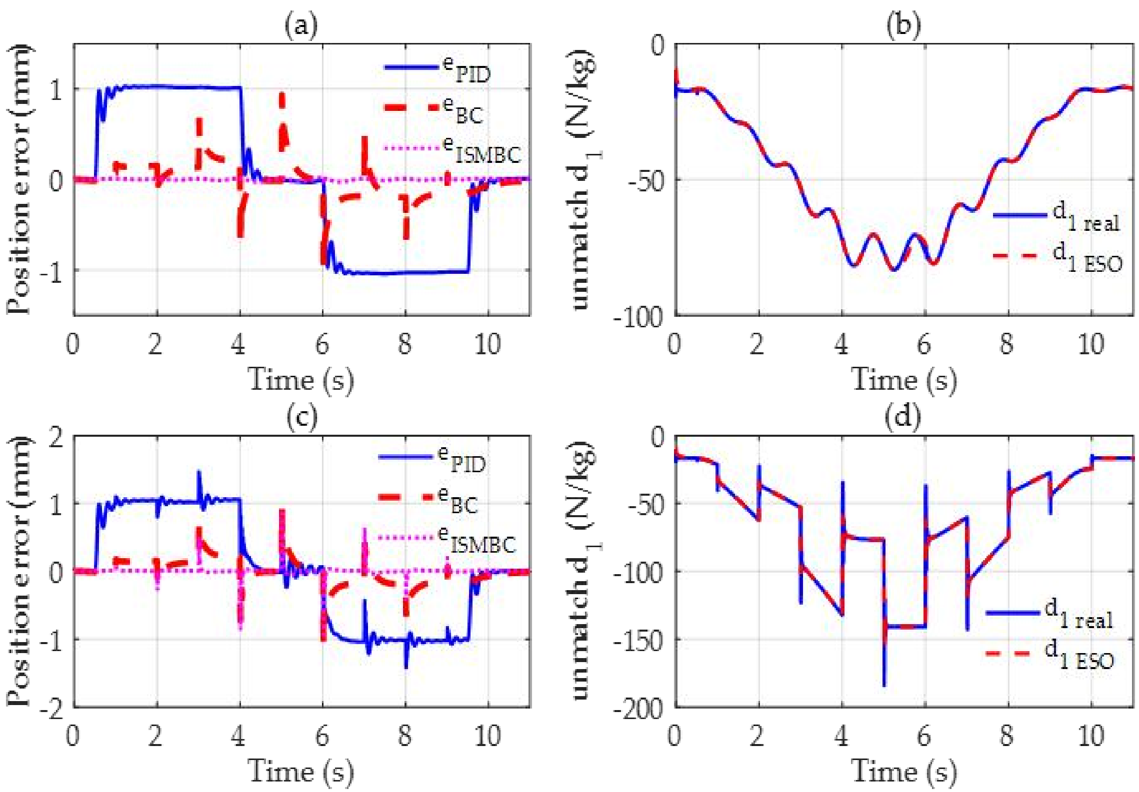
With loads of 100kg, 200kg and 300kg, control precisions is given of the three control, as shown in Figure 10.



It can be seen that as the load increases, the maximum tracking error gradually decreases with the ISMBC controller, but other controllers gradually increase. Thus, the results indicate that the integral sliding mode control can enhance the robustness.

Figure 10. Position tracking error change of three controllers and external disturbance observation with varying loads: (a) position tracking errors of PID; (b) position tracking errors of BC; (c) position tracking errors of ISMBC; (d) estimation of external disturbances with varying loads.

3.5 With varying disturbances



To compare the anti-disturbance ability of the three controllers, sine disturbance and pulse disturbance are applied during the crane movement

With varying external disturbance based on sine plus pulse, the ISMBC controller shows the strongest anti-disturbance ability.

Figure 11. Simulation results of the three controllers with varying disturbances: (a) control errors with sine disturbance; (b) unmatching disturbance observed value with sine disturbance; (c) control errors with sine disturbance plus pulse disturbance; (d) unmatching disturbance observed value with sine disturbance plus pulse disturbance.

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4. Conclusion

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PID VS BC VS ISMBC

Criteria	PID	BC	ISMBC
Precision	★	★ ★	★ ★ ★
Stability	★	★ ★	★ ★ ★
Robustness	★ ★	★	★ ★ ★

4. Conclusion

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In summary, the backstepping design can improve the control precision and response speed of the EHA, but the anti-disturbance ability just a little bit worse. To improve the anti-disturbance ability, the integral sliding mode control is introduced in the backstepping design. Analysis and simulation results indicate that the proposed ISMBC controller not only further improve the control accuracy, but also can enhance the EHA stability and robustness.

Due to lacking experimental verification and the proposed controller relies on accurate system parameters in this study, we will devote ourselves to building a test platform and implementing adaptive control in the following research.

Thank You !