Lithographic Trajectory Planning for Residual Vibration Suppression: An Asymmetric S-Curve Method

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Contents

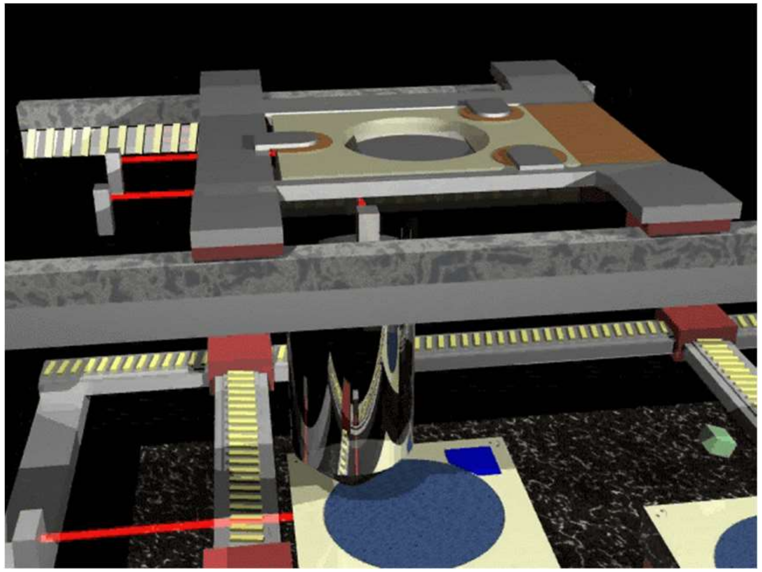
1. Lithography and Motion Control

- **Lithography Tool: CD, Overlay, Throughput**
- **Wafer & Reticle Stages: MSD ,MA, ST**

MSD: High-frequency component of synchronization error, MSD<7nm@CD<38nm

MA: Low-frequency component of synchronization error, MA<1nm@Overlay<4nm

ST: settling time (constant velocity phase, positioning phase), ST<10ms



Very high dynamic motion

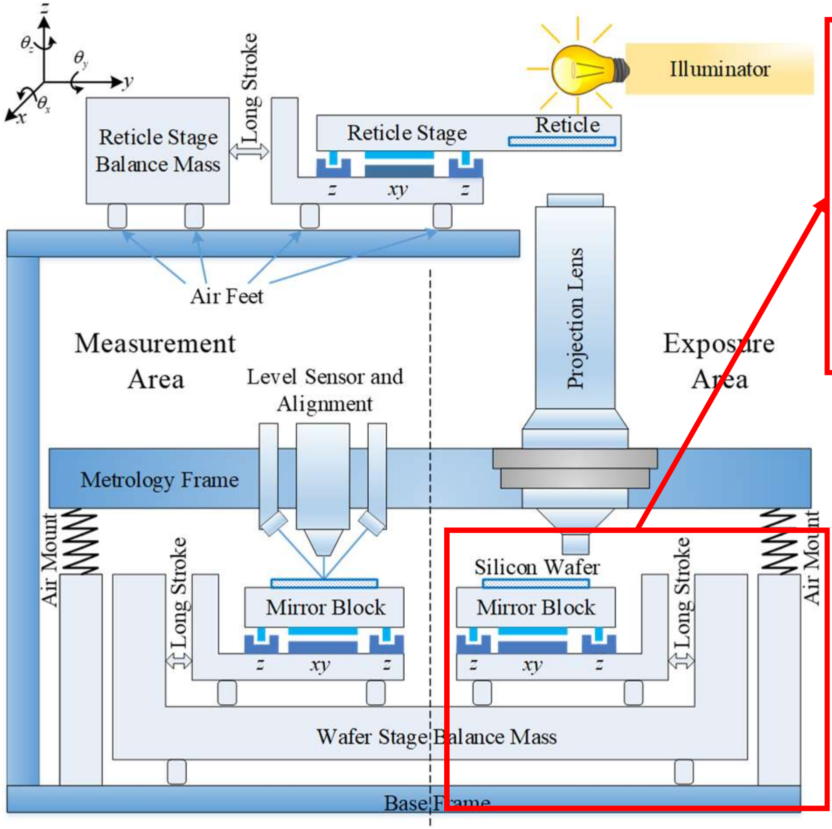
High speed: V_{max}=0.7m/s

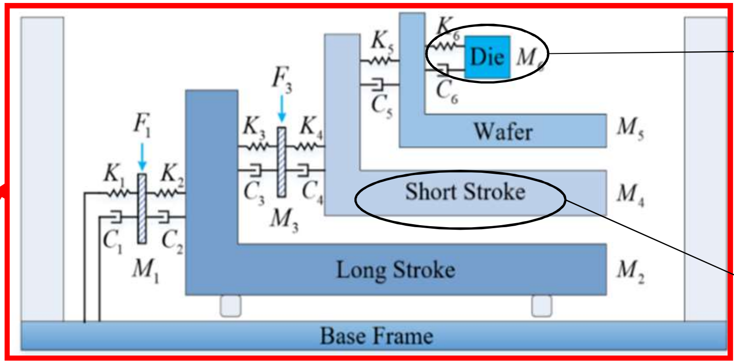
High acceleration: A_{max}=25m/s^2

Very high servo accuracy

Very short settling time

1. Lithography and Motion Control



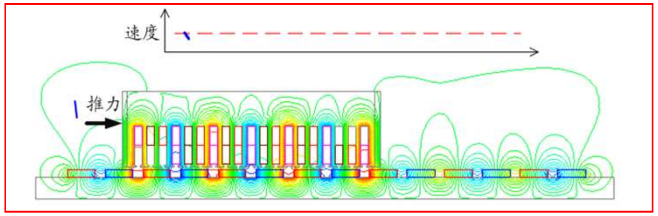


Point of interest

Multi-rigid-body system

Measured and actively controlled point

Magnetic disturbance



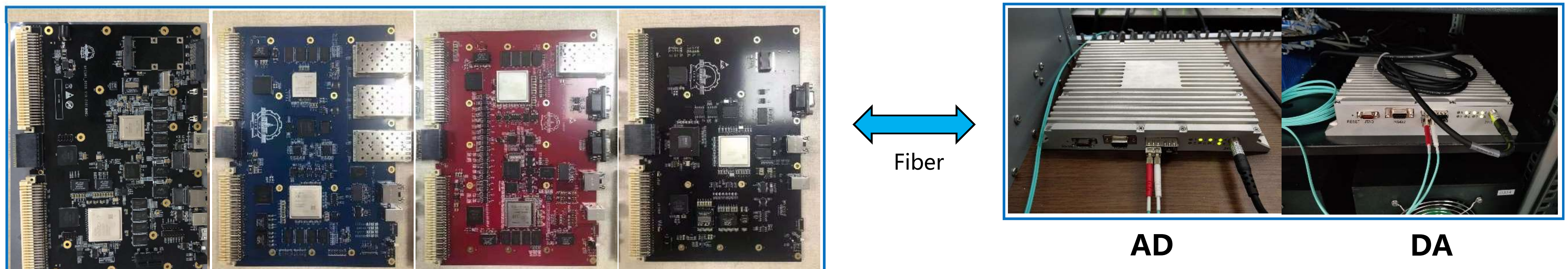
Cable force

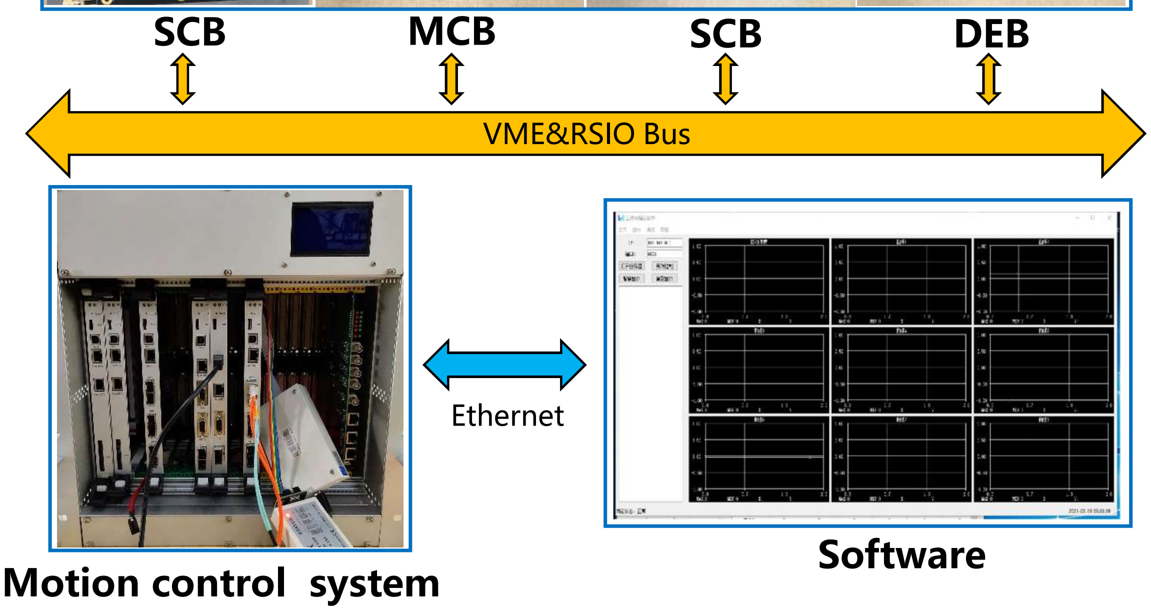
Large amount of sensors (interferometers, eddy current sensors, linear encoders …)
Large amount of actuators (planar motors, voice coil motors, linear motors …)

Very complex measurement & control system

1. Lithography and Motion Control

◻ Motion Control System: Hardware & Software





- ✓ Multi-task scheduling
- ✓ Multi-axis coordination
- ✓ Sensor data acquisition
- ✓ Control computation
- ✓ Actuator command transmission

1. Lithography and Motion Control

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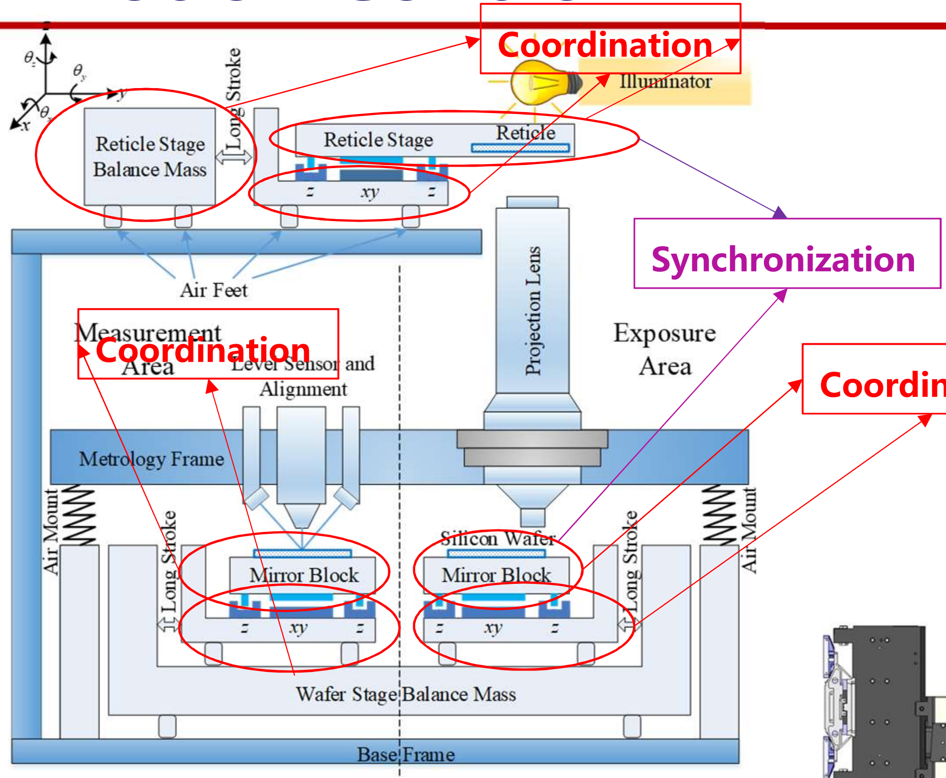
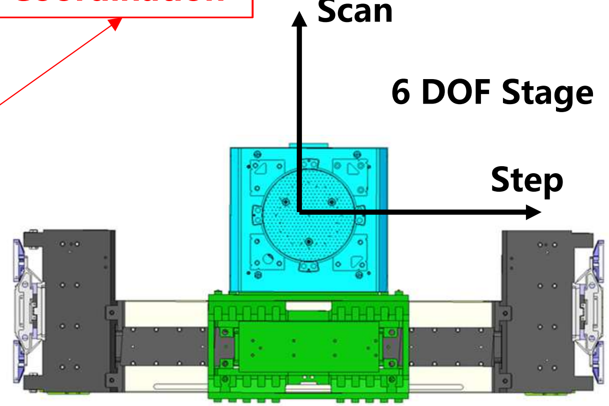
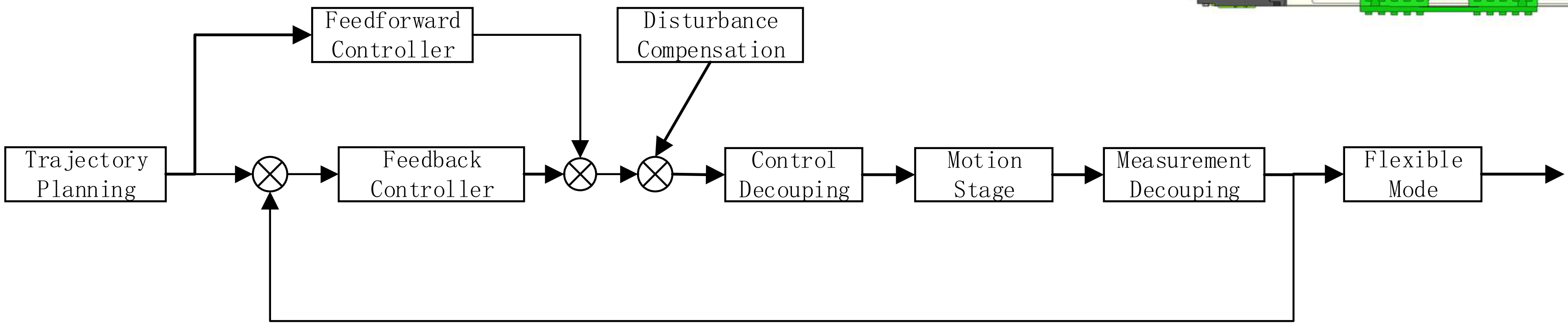
□ Firmware

- ✓ Multi-stage coordination
- ✓ Multi-DOF decoupling
- ✓ Feedback control
- ✓ Feedforward control
- ✓ Disturbance compensation
- ✓ Iterative tuning & learning
- ✓ Trajectory planning







1. Lithography and Motion Control

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[1] Zhao H, **<u>Li L*</u>**, Liu Y. Iterative Control Decoupling Tuning by Feedforward Compensation for Precision Motion Stage[C]//2023 IEEE 12th Data Driven Control and Learning Systems Conference (DDCLS). IEEE, 2023: 1812-1817. Oral presentation

[2] **<u>Li L</u>**, Zhao H, Song F. Enhancing projection based iterative learning control: A set-membership approach[J]. ISA transactions, 2023, 10.1016/j.isatra.2023.06.032. ***Top , JCR Q1, IF=7.3***

[3] Song F, **<u>Li L*</u>**, Liu Y, et al. Singular value decomposition based learning identification for linear time-varying systems: From recursion to iteration[J]. International Journal of Robust and Nonlinear Control, 2023,32(12): 6986-7003. JCR Q1, IF=3.9

[4] **<u>Li L</u>**, Zhao H, Liu Y. Self-Tuning Nonlinear Iterative Learning for a Precision Testing Stage: A Set-Membership Approach[J]. **<u>IEEE Transactions on Industrial Informatics</u>**, 2023,19(7):7995-8006. ***Top, JCR Q1, IF=12.3***

[5] **<u>Li L</u>**, Liu Y, Fu X, et al. Finite time stable inversion in discrete frequency domain: Accuracy analysis, improvement and application to wafer stage[J]. ISA transactions, 2023, 132: 462-476. ***Top , JCR Q1, IF=7.3***

[6] Liu Y, **<u>Li Li</u>**, Chen S, Tan J. Data and mechanism hybrid driven intelligent ultra-precision technology [C]// IFMI & ISPEMI 2022. ***Invited presentation***

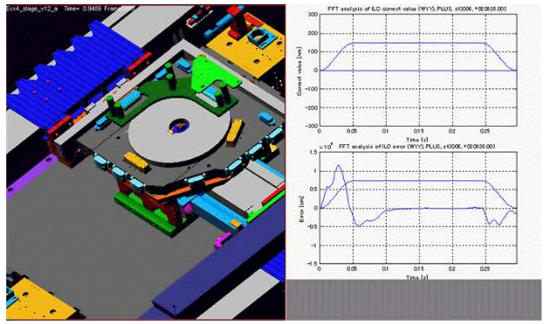
[7]刘杨,**<u>李理*</u>**,陈思文,等. 面向IC光刻的超精密运动台控制技术[J]. 激光与光电子学进展, 2022, 59(09): 233-253. ***Invited survey.***

[8] **<u>Li L</u>**, Liu Y, Li L, et al. Kalman-filtering-based iterative feedforward tuning in presence of stochastic noise: With application to a wafer stage[J]. **<u>IEEE Transactions on Industrial Informatics</u>**, 2019, 15(11): 5816-5826. ***Top, JCR Q1, IF=12.3***

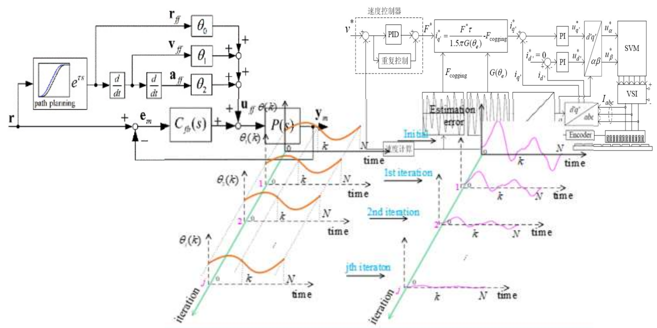
[9] **<u>Li L</u>**, Liu Y, Yang Z, et al. Method to improve convergence performance of iterative learning control systems with bounded noise[J]. Journal of the Franklin Institute, 2020, 357(3): 1644-1670. ***JCR Q1, IF=4.1***

[10] **<u>Li L</u>**, Liu Y, Yang Z, et al. Mean-square error constrained approach to robust stochastic iterative learning control[J]. IET Control Theory & Applications, 2018, 12(1): 38-44. ***JCR Q1, IF=2.6***

Iterative learning

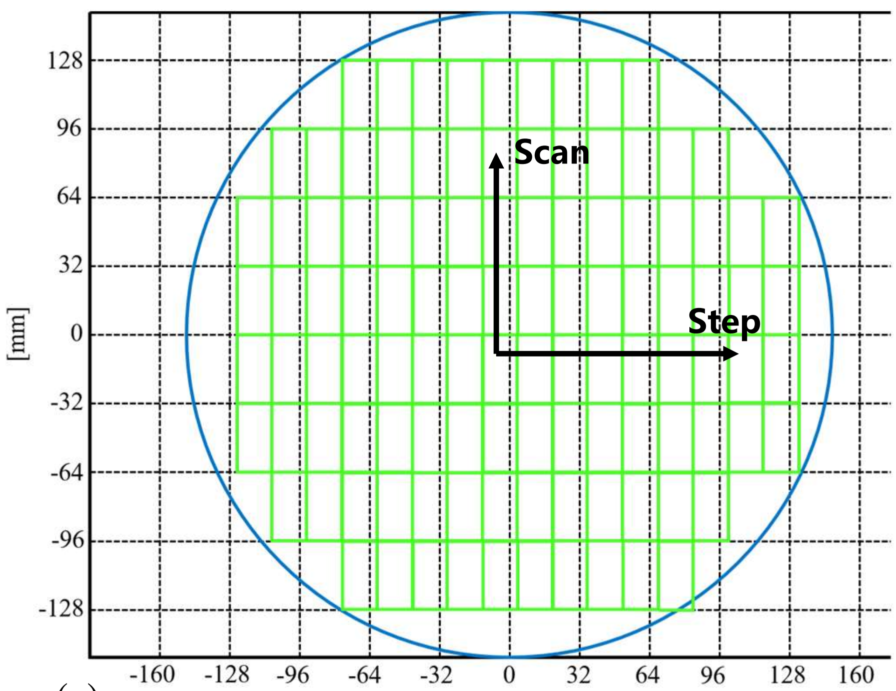


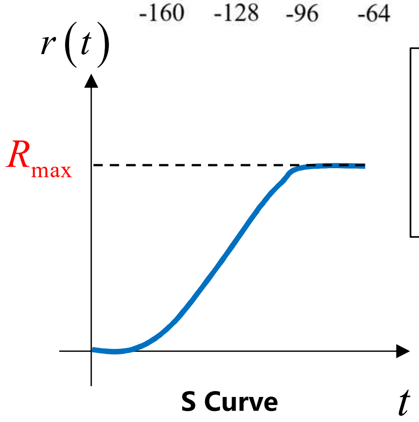
Iterative tuning



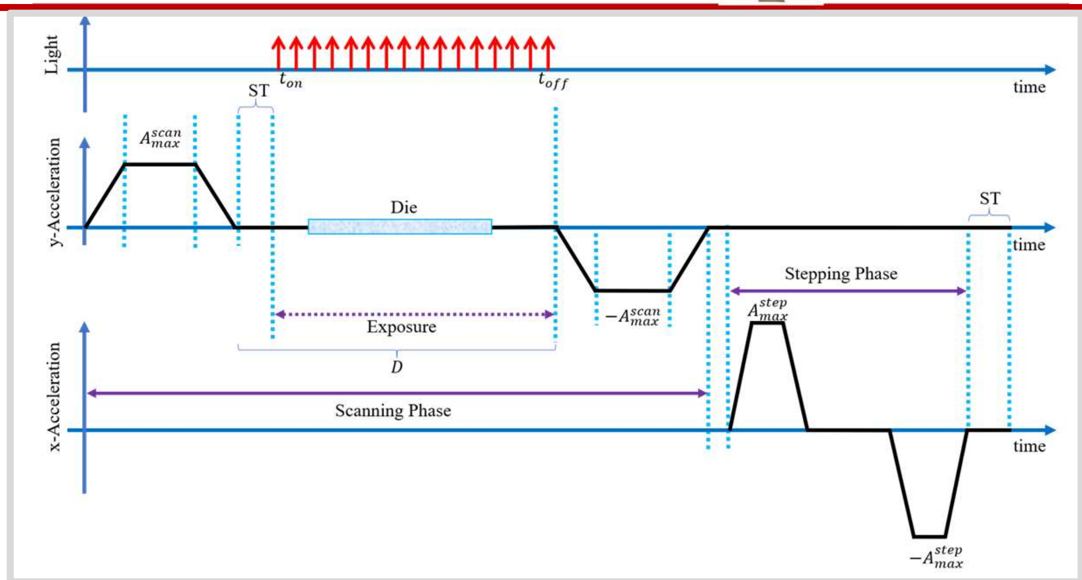
4 top journal paper
1 invited presentation
1 invited survey paper

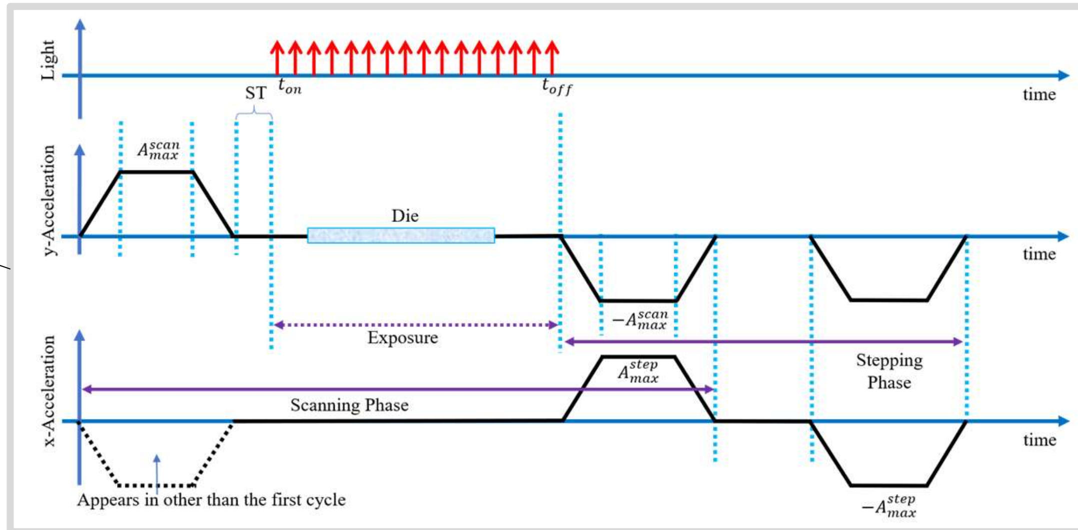
2. Step & Scan Trajectory





Allow to adjust the trajectory to realize higher performance without increasing total time





3. Symmetric S-curve Planning

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Time-domain representations of symmetric S-curves

3rd order S-curve : ***7*** time intervals can be defined from ***Jerk*** profile

$$t_1 = t_3 = t_5 = t_7 = \frac{A_{\max}}{J_{\max}},\ t_2 = t_6 = \frac{V_{\max}}{A_{\max}} - t_1,\ t_4 \approx \frac{R_{\max}}{V_{\max}} - t_2 - 2t_1$$

4th order S-curve : ***15*** time intervals can be defined from ***Snap*** profile

$$t_1 = t_3 = t_5 = t_7 = t_9 = t_{11} = t_{13} = t_{15} = \frac{J_{\max}}{S_{\max}},\ t_2 = t_6 = t_{10} = t_{14} = \frac{A_{\max}}{J_{\max}} - t_1,$$

$$t_4 = t_{12} \approx \frac{V_{\max}}{A_{\max}} - 2t_1 - t_2,\ t_8 \approx \frac{R_{\max}}{V_{\max}} - t_4 - 2t_2 - 4t_1$$

5th order S-curve : ***31*** time intervals can be defined from ***Crackle*** profile

$$t_1 = t_3 = t_5 = t_7 = t_9 = t_{11} = t_{13} = t_{15} = t_{17} = t_{19} = t_{21} = t_{23} = t_{25} = t_{27} = t_{29} = t_{31} = \frac{S_{\max}}{C_{\max}},$$

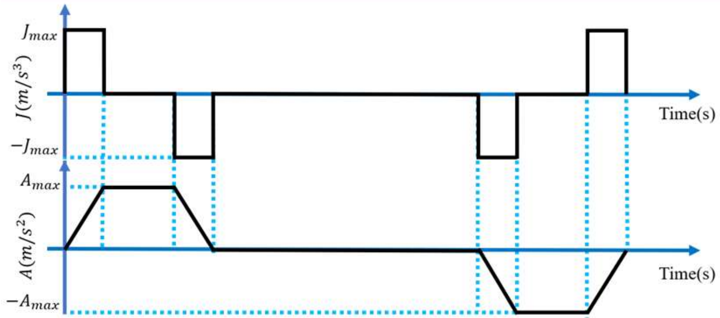
$$t_2 = t_6 = t_{10} = t_{14} = t_{18} = t_{22} = t_{26} = t_{30} = \frac{J_{\max}}{S_{\max}} - t_1,\ t_4 = t_{12} = t_{20} = t_{28} \approx \frac{A_{\max}}{J_{\max}} - 2t_1 - t_2,$$

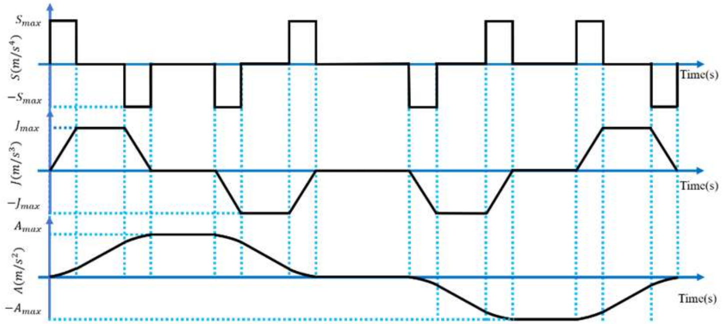
$$t_8 = t_{24} \approx \frac{V_{\max}}{A_{\max}} - t_4 - 2t_2 - 4t_1,\ t_{16} \approx \frac{S_{\max}}{V_{\max}} - t_8 - 2t_4 - 4t_2 - 8t_1,$$

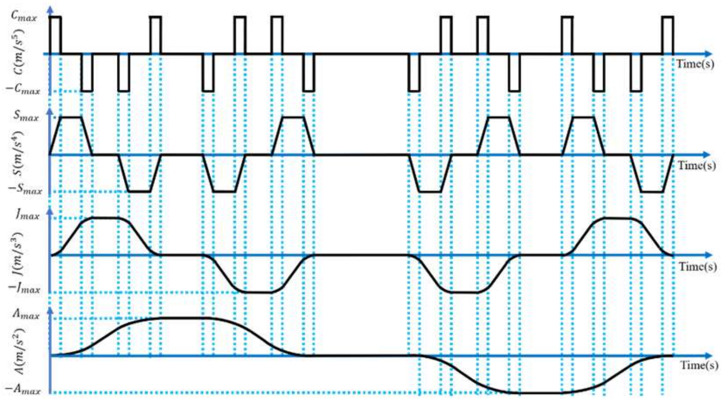
Conclusions:

① **q^{th} order S-curve:** q times integration of square wave

② Time intervals are determined by ***trajectory parameters***







3. Symmetric S-curve Planning

Laplace transformations of symmetric S-curves

$$3^{rd}\ order: R(s) = \frac{J_{max}}{s}\frac{(1-e^{-A_{max}/J_{max}s})(1-e^{-V_{max}/A_{max}s})(1-e^{-R_{max}/V_{max}s})}{s^3}$$

$$= \frac{R_{max}}{s}\left(\frac{J_{max}}{A_{max}}\frac{1-e^{-A_{max}/J_{max}s}}{s}\right)\left(\frac{A_{max}}{V_{max}}\frac{1-e^{-V_{max}/A_{max}s}}{s}\right)\left(\frac{V_{max}}{R_{max}}\frac{1-e^{-R_{max}/V_{max}s}}{s}\right)$$

$$4^{th}\ order: R(s) = \frac{S_{max}}{s}\frac{(1-e^{-J_{max}/S_{max}s})(1-e^{-A_{max}/J_{max}s})(1-e^{-V_{max}/A_{max}s})(1-e^{-R_{max}/V_{max}s})}{s^4}$$

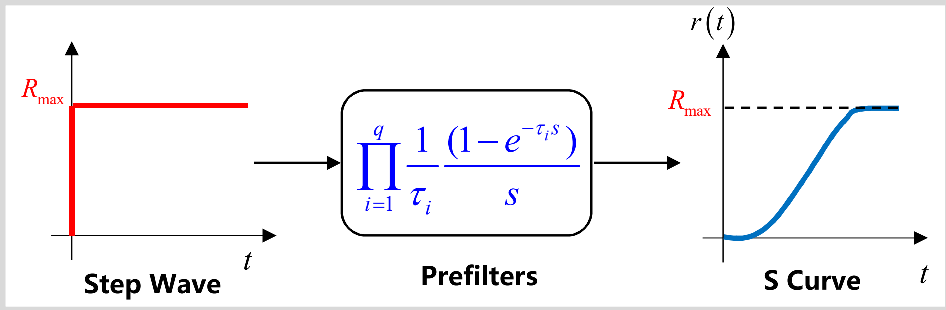
$$= \frac{R_{max}}{s}\left(\frac{S_{max}}{J_{max}}\frac{1-e^{-J_{max}/S_{max}s}}{s}\right)\left(\frac{J_{max}}{A_{max}}\frac{1-e^{-A_{max}/J_{max}s}}{s}\right)\left(\frac{A_{max}}{V_{max}}\frac{1-e^{-V_{max}/A_{max}s}}{s}\right)\left(\frac{V_{max}}{R_{max}}\frac{1-e^{-R_{max}/V_{max}s}}{s}\right)$$

$$5^{th}\ order: R(s) = \frac{C_{max}}{s}\frac{(1-e^{-S_{max}/C_{max}s})(1-e^{-J_{max}/S_{max}s})(1-e^{-A_{max}/J_{max}s})(1-e^{-V_{max}/A_{max}s})(1-e^{-R_{max}/V_{max}s})}{s^5}$$

$$= \frac{R_{max}}{s}\left(\frac{C_{max}}{S_{max}}\frac{1-e^{-S_{max}/C_{max}s}}{s}\right)\left(\frac{S_{max}}{J_{max}}\frac{1-e^{-J_{max}/S_{max}s}}{s}\right)\left(\frac{J_{max}}{A_{max}}\frac{1-e^{-A_{max}/J_{max}s}}{s}\right)\left(\frac{A_{max}}{V_{max}}\frac{1-e^{-V_{max}/A_{max}s}}{s}\right)\left(\frac{V_{max}}{R_{max}}\frac{1-e^{-R_{max}/V_{max}s}}{s}\right)$$

$$\vdots$$

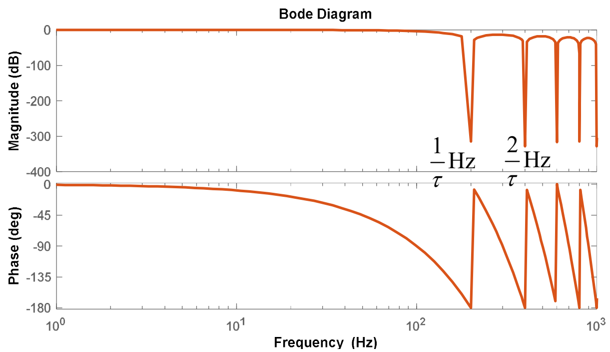
$$q^{th}\ order: R(s) = \frac{R_{max}}{s}\prod_{i=1}^{q}\frac{1}{\tau_i}\frac{(1-e^{-\tau_i s})}{s}$$



Conclusions:

① **S-curve:** Filtered step wave

② **Prefilter:** 1st order low-pass filter with specific frequency ($\frac{k}{\tau}$Hz) suppression



3. Symmetric S-curve Planning

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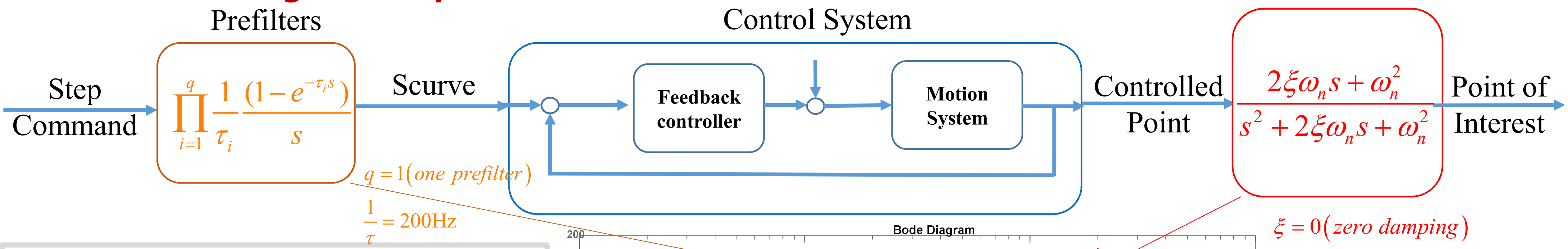
Parameter design: zero-pole cancelation



$\xi = 0(zero\ damping)$

$\frac{\omega_n}{2\pi} = f_n = 200\text{Hz}$

Conclusion :

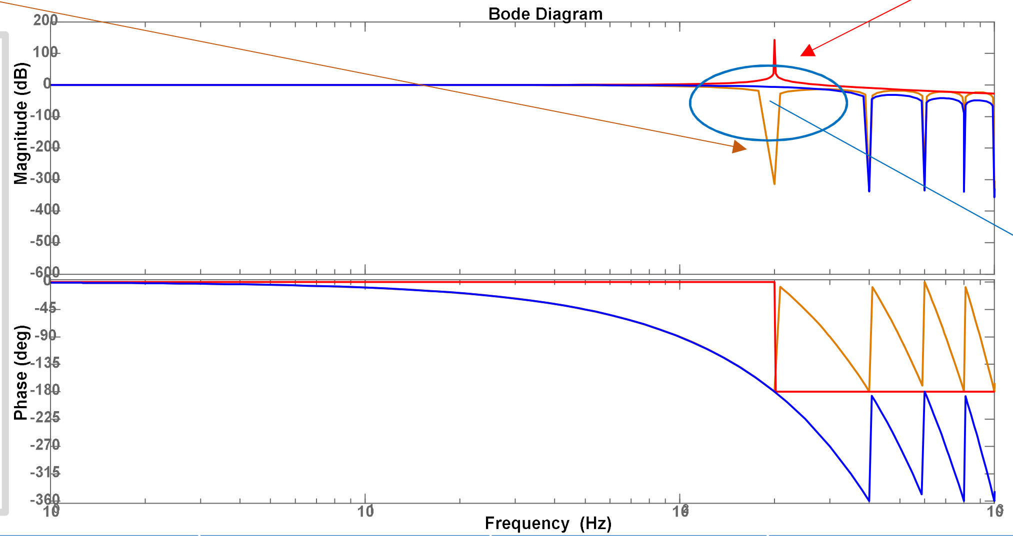
For 4[th] order S-curve,

$$\tau_i \in \left[\frac{J_{max}}{S_{max}}, \frac{A_{max}}{J_{max}}, \frac{V_{max}}{A_{max}}, \frac{R_{max}}{V_{max}}\right]$$

zero-pole cancelation: $\frac{k}{\tau_i} = f_{n,j}$

R_{max}, V_{max} are fixed $-$ 1 zero is fixed

$A_{max}, J_{max}, S_{max}$ can be tuned $-$ 3 zeros can be designed to compensate poles of flexible modes



$$\frac{1}{200}\frac{(1-e^{-\frac{1}{200}s})}{s} \times \frac{(2\pi\times 200)^2}{s^2+(2\pi\times 200)^2}$$

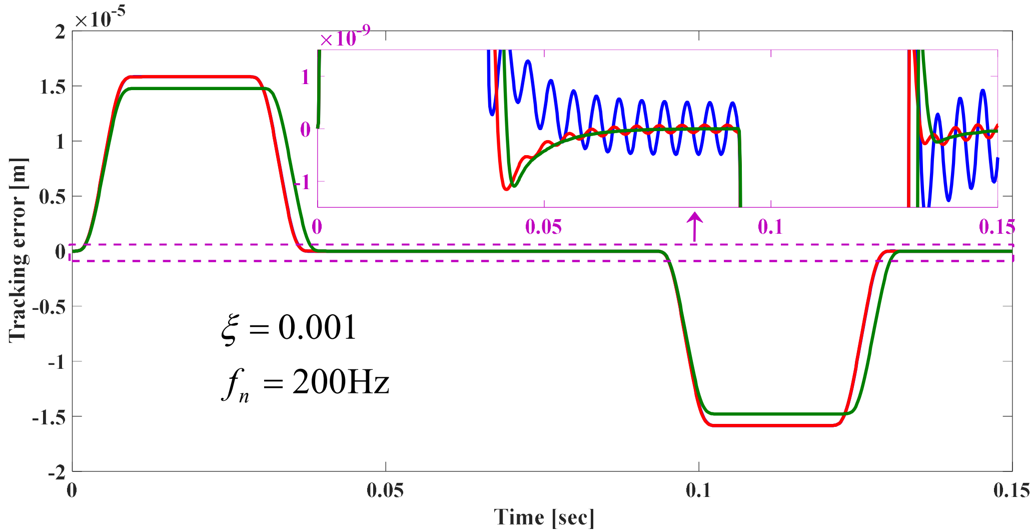
well compensated

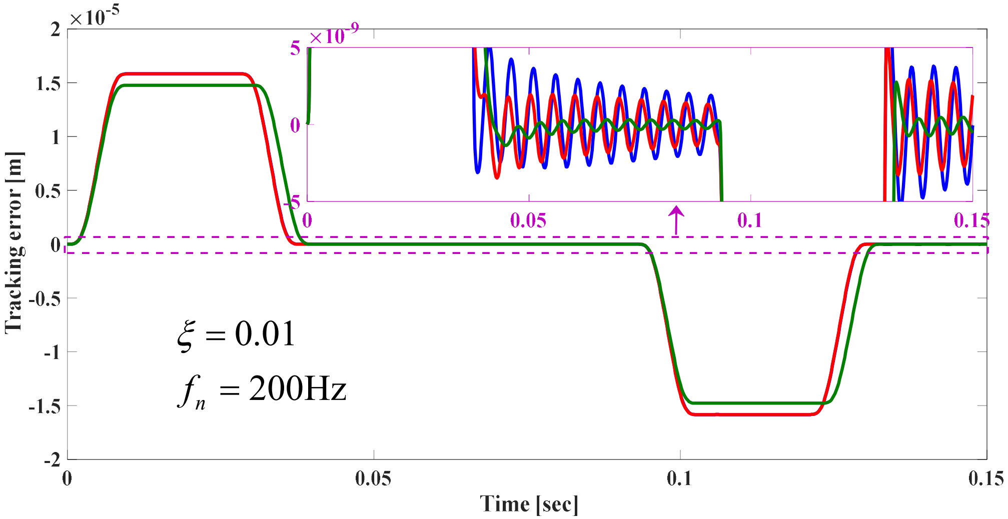
R_{max}	V_{max}	A_{max}	J_{max}	S_{max}	C_{max}
Die size	Throughput Sensor limit Actuator limit Light source	Throughput Actuator limit Residual vibration suppression	Throughput Residual vibration suppression	Throughput Residual vibration suppression	Throughput Residual vibration suppression

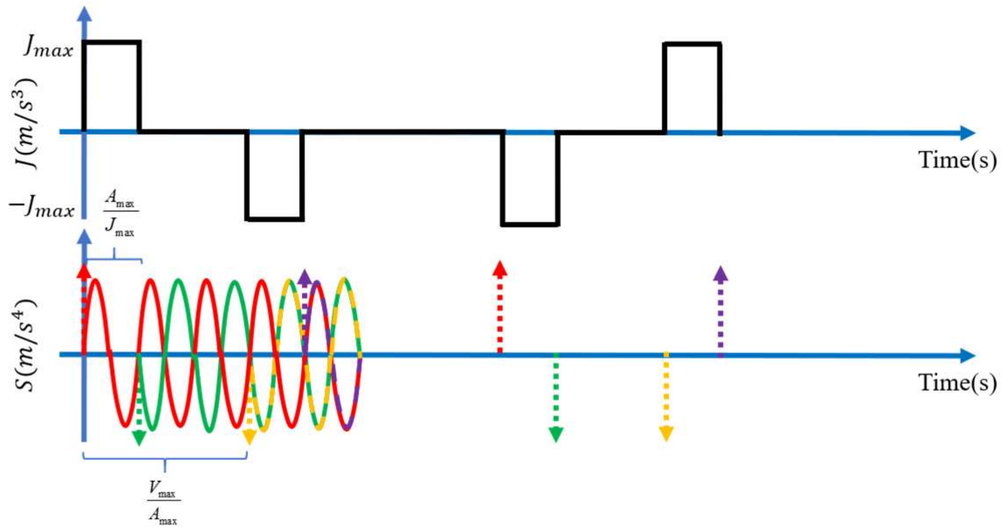
3. Symmetric S-curve Planning

Results & discussions

R_{max}	V_{max}	A_{max}	J_{max}	S_{max}
0.065	0.7	25	4950	$J_{max} \times f_n = 990000$
0.065	0.7	25	$A_{max} \times f_n = 5000$	$J_{max} \times f_n = 1000000$
0.065	0.7	$\frac{V_{max} \times f_n}{6} = \frac{70}{3}$	$A_{max} \times f_n = \frac{14000}{3}$	$J_{max} \times f_n = \frac{2800000}{3}$

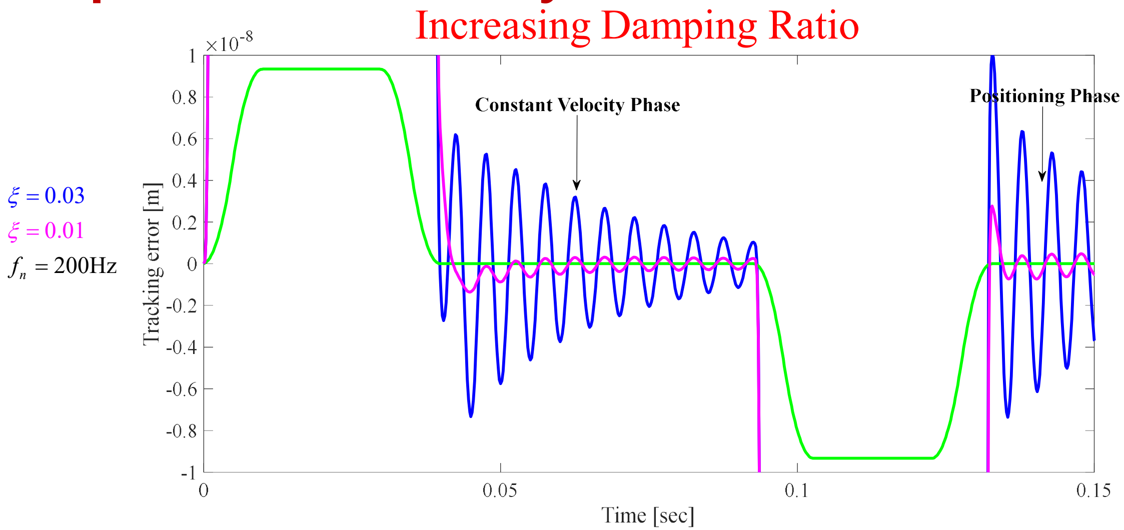


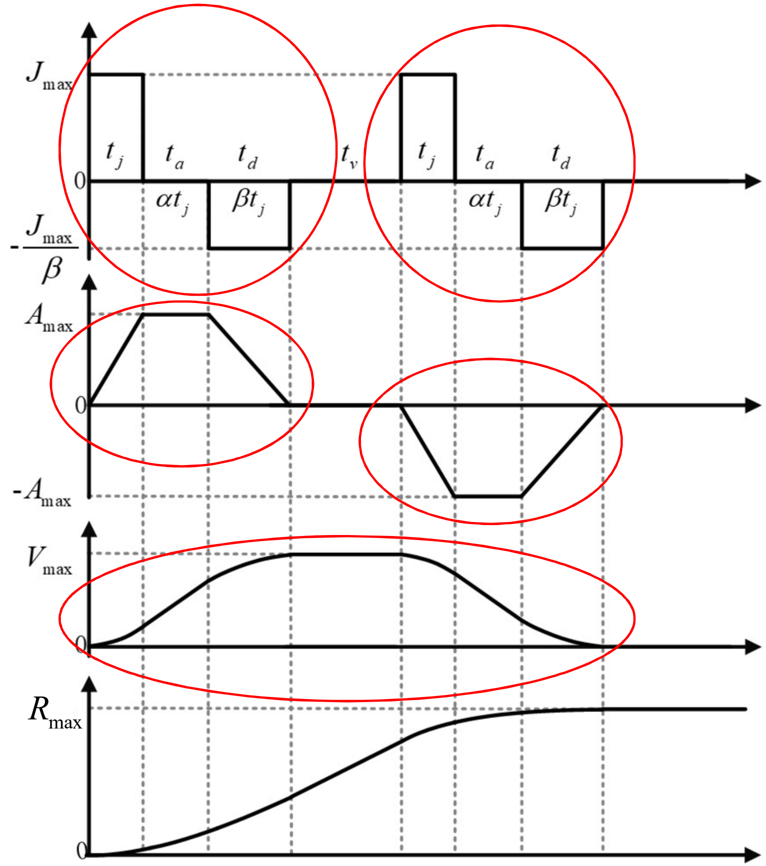




4. Asymmetric S-curve Planning

Representations of asymmetric S-curves

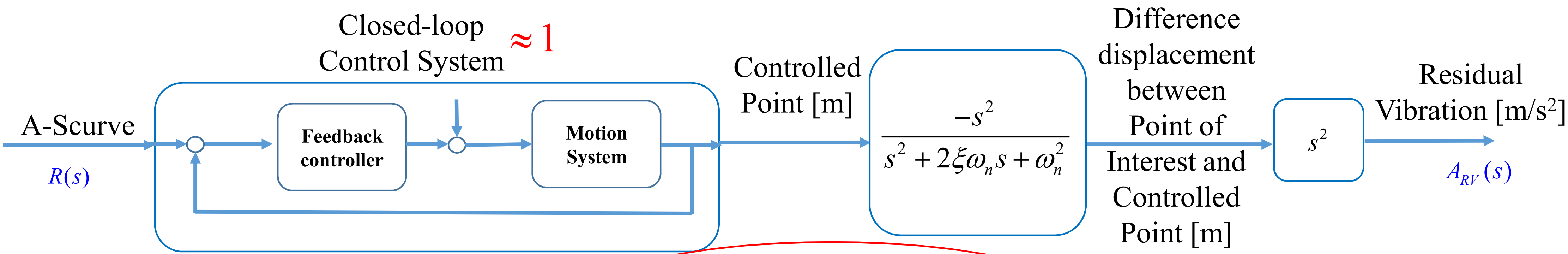




$$\begin{cases} \textit{Constant Velocity Phase}: R_c(s)=\dfrac{J_{max}}{s}\dfrac{1-e^{-\frac{t_m}{1+2\alpha+\beta}s}-\dfrac{1}{\beta}e^{-\frac{t_m(1+\alpha)}{1+2\alpha+\beta}s}+\dfrac{1}{\beta}e^{-\frac{t_m(1+\alpha+\beta)}{1+2\alpha+\beta}s}}{s^3} \\ \textit{Positioning Phase}: R_p(s)=\dfrac{J_{max}}{s}\dfrac{\left(1-e^{-\frac{t_m}{1+2\alpha+\beta}s}-\dfrac{1}{\beta}e^{-\frac{t_m(1+\alpha)}{1+2\alpha+\beta}s}+\dfrac{1}{\beta}e^{-\frac{t_m(1+\alpha+\beta)}{1+2\alpha+\beta}s}\right)\left(1-e^{-\frac{t_m(1+\alpha+\beta)+t_v}{1+2\alpha+\beta}s}\right)}{s^3} \end{cases}$$

$$\begin{cases} t_m = 2\dfrac{V_{max}}{A_{max}} \\ t_v = \dfrac{R_{max}}{V_{max}} - \dfrac{1+\alpha+\beta}{1+2\alpha+\beta}\dfrac{t_m}{2} \end{cases}$$

4. Asymmetric S-curve Planning



Constant Velocity Phase: $A_{RV-c}(s) = -\frac{J_{\max}}{s^2+2\xi\omega_n s+\omega_n^2}\left(1-e^{-\frac{t_m}{1+2\alpha+\beta}s}-\frac{1}{\beta}e^{-\frac{t_m(1+\alpha)}{1+2\alpha+\beta}s}+\frac{1}{\beta}e^{-\frac{t_m(1+\alpha+\beta)}{1+2\alpha+\beta}s}\right)$

Positioning Phase: $A_{RV-p}(s) = -\frac{J_{\max}}{s^2+2\xi\omega_n s+\omega_n^2}\left(1-e^{-\frac{t_m}{1+2\alpha+\beta}s}-\frac{1}{\beta}e^{-\frac{t_m(1+\alpha)}{1+2\alpha+\beta}s}+\frac{1}{\beta}e^{-\frac{t_m(1+\alpha+\beta)}{1+2\alpha+\beta}s}\right)\left(1-e^{-\frac{t_m(1+\alpha+\beta)+t_v}{1+2\alpha+\beta}s}\right)$

$s_{fm} = -\xi\omega_n \pm \omega_d j$

$\omega_d = \sqrt{1-\xi}\omega_n$

$$\left(1-e^{-\frac{t_m}{1+2\alpha+\beta}s}-\frac{1}{\beta}e^{-\frac{t_m(1+\alpha)}{1+2\alpha+\beta}s}+\frac{1}{\beta}e^{-\frac{t_m(1+\alpha+\beta)}{1+2\alpha+\beta}s}\right)\Big|_{s=s_{fm}}$$

$$=1-e^{\frac{t_m\xi\omega_n}{1+2\alpha+\beta}}\cos\left(\frac{t_m\omega_d}{1+2\alpha+\beta}\right)-\frac{1}{\beta}e^{\frac{t_m(1+\alpha)\xi\omega_n}{1+2\alpha+\beta}}\cos\left(\frac{t_m(1+\alpha)\omega_d}{1+2\alpha+\beta}\right)+\frac{1}{\beta}e^{\frac{t_m(1+\alpha+\beta)\xi\omega_n}{1+2\alpha+\beta}}\cos\left(\frac{t_m(1+\alpha+\beta)\omega_d}{1+2\alpha+\beta}\right)$$

$$\pm\left(e^{\frac{t_m\xi\omega_n}{1+2\alpha+\beta}}\sin\left(\frac{t_m\omega_d}{1+2\alpha+\beta}\right)+\frac{1}{\beta}e^{\frac{t_m(1+\alpha)\xi\omega_n}{1+2\alpha+\beta}}\sin\left(\frac{t_m(1+\alpha)\omega_d}{1+2\alpha+\beta}\right)-\frac{1}{\beta}e^{\frac{t_m(1+\alpha+\beta)\xi\omega_n}{1+2\alpha+\beta}}\sin\left(\frac{t_m(1+\alpha+\beta)\omega_d}{1+2\alpha+\beta}\right)\right)j$$

$$=\mathrm{Re}(\alpha,\beta)\pm\mathrm{Im}(\alpha,\beta)j$$

zero-pole cancelation:

$\mathrm{Re}(\alpha,\beta)=0$

$\mathrm{Im}(\alpha,\beta)=0$

4. Asymmetric S-curve Planning

Solve the following equations with respect to α and β

$$\mathrm{Re}(\alpha,\beta)=1-e^{\frac{t_m\xi\omega_n}{1+2\alpha+\beta}}\cos\left(\frac{t_m\omega_d}{1+2\alpha+\beta}\right)-\frac{1}{\beta}e^{\frac{t_m(1+\alpha)\xi\omega_n}{1+2\alpha+\beta}}\cos\left(\frac{t_m(1+\alpha)\omega_d}{1+2\alpha+\beta}\right)+\frac{1}{\beta}e^{\frac{t_m(1+\alpha+\beta)\xi\omega_n}{1+2\alpha+\beta}}\cos\left(\frac{t_m(1+\alpha+\beta)\omega_d}{1+2\alpha+\beta}\right)=0$$

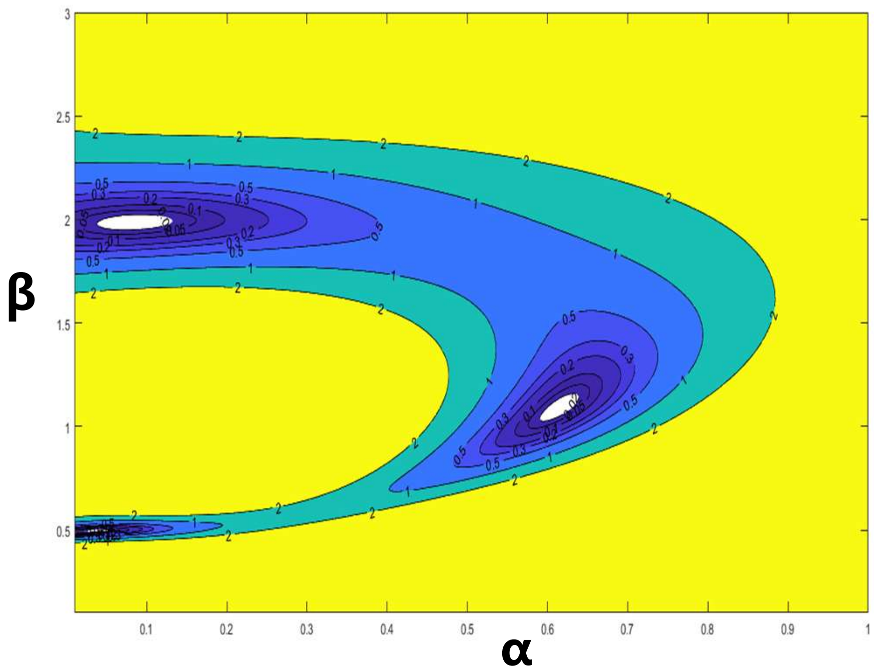
$$\mathrm{Im}(\alpha,\beta)=\left(e^{\frac{t_m\xi\omega_n}{1+2\alpha+\beta}}\sin\left(\frac{t_m\omega_d}{1+2\alpha+\beta}\right)+\frac{1}{\beta}e^{\frac{t_m(1+\alpha)\xi\omega_n}{1+2\alpha+\beta}}\sin\left(\frac{t_m(1+\alpha)\omega_d}{1+2\alpha+\beta}\right)-\frac{1}{\beta}e^{\frac{t_m(1+\alpha+\beta)\xi\omega_n}{1+2\alpha+\beta}}\sin\left(\frac{t_m(1+\alpha+\beta)\omega_d}{1+2\alpha+\beta}\right)\right)=0$$

Newton Iteration Method

$$\begin{cases} C\big|_{(\alpha,\beta)} \approx C\big|_{(\alpha_0,\beta_0)} + C_\alpha'\big|_{(\alpha_0,\beta_0)}\bullet(\alpha-\alpha_0)+C_\beta'\big|_{(\alpha_0,\beta_0)}\bullet(\beta-\beta_0) \\ S\big|_{(\alpha,\beta)} \approx S\big|_{(\alpha_0,\beta_0)} + S_\alpha'\big|_{(\alpha_0,\beta_0)}\bullet(\alpha-\alpha_0)+S_\beta'\big|_{(\alpha_0,\beta_0)}\bullet(\beta-\beta_0) \end{cases}$$

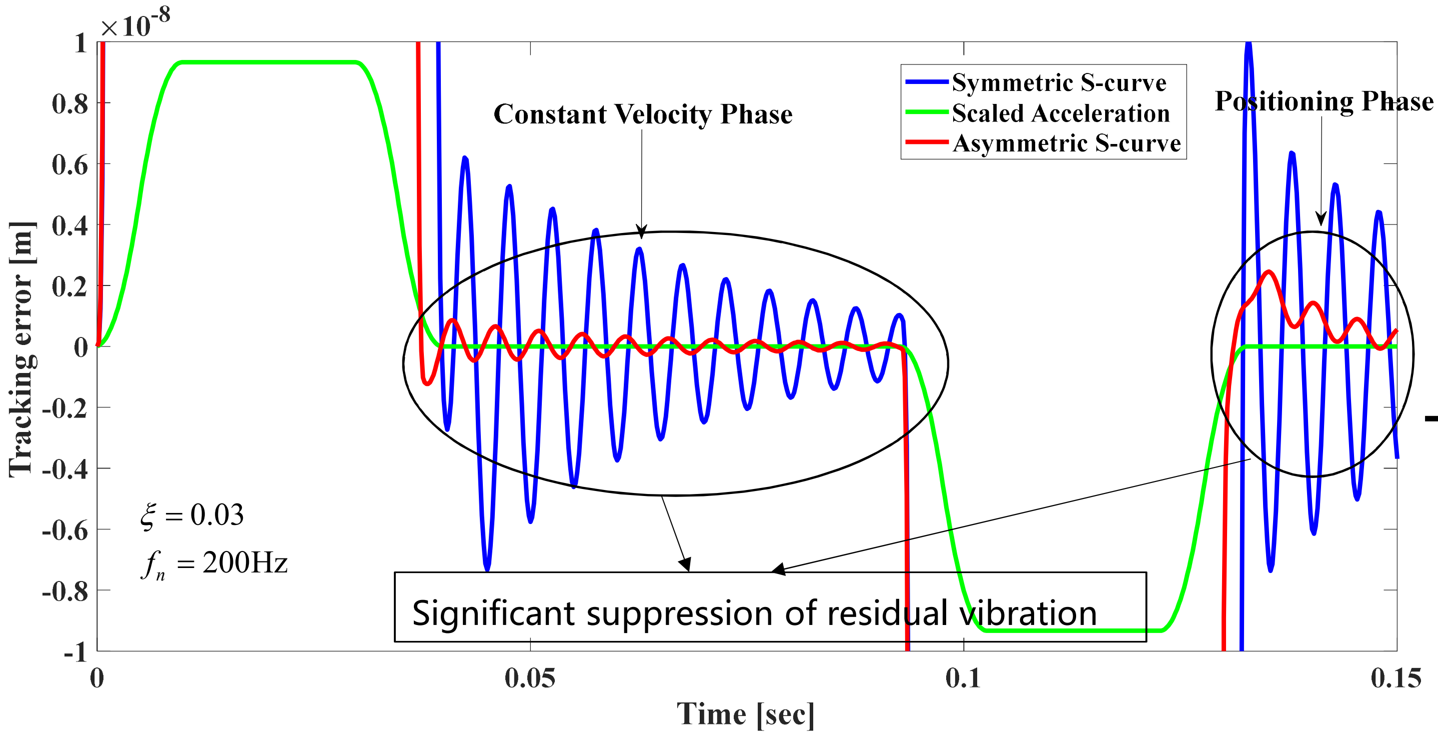
$$\begin{cases} C\big|_{(\alpha_0,\beta_0)} + C_\alpha'\big|_{(\alpha_0,\beta_0)}\bullet(\alpha-\alpha_0)+C_\beta'\big|_{(\alpha_0,\beta_0)}\bullet(\beta-\beta_0)=0 \\ S\big|_{(\alpha_0,\beta_0)} + S_\alpha'\big|_{(\alpha_0,\beta_0)}\bullet(\alpha-\alpha_0)+S_\beta'\big|_{(\alpha_0,\beta_0)}\bullet(\beta-\beta_0)=0 \end{cases}$$

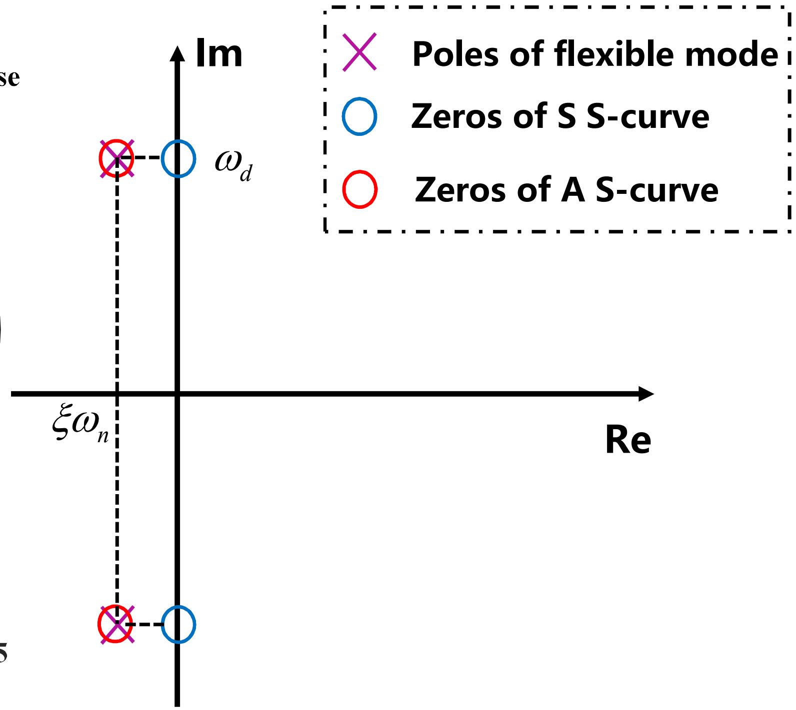
$$\begin{cases} \alpha_{k+1}=\alpha_k+\dfrac{CS_\beta'-SC_\beta'}{S_\alpha'C_\beta'-C_\alpha'S_\beta'}\Big|_{(\alpha_k,\beta_k)} \\ \beta_{k+1}=\beta_k+\dfrac{SC_\alpha'-CS_\alpha'}{S_\alpha'C_\beta'-C_\alpha'S_\beta'}\Big|_{(\alpha_k,\beta_k)} \end{cases}$$



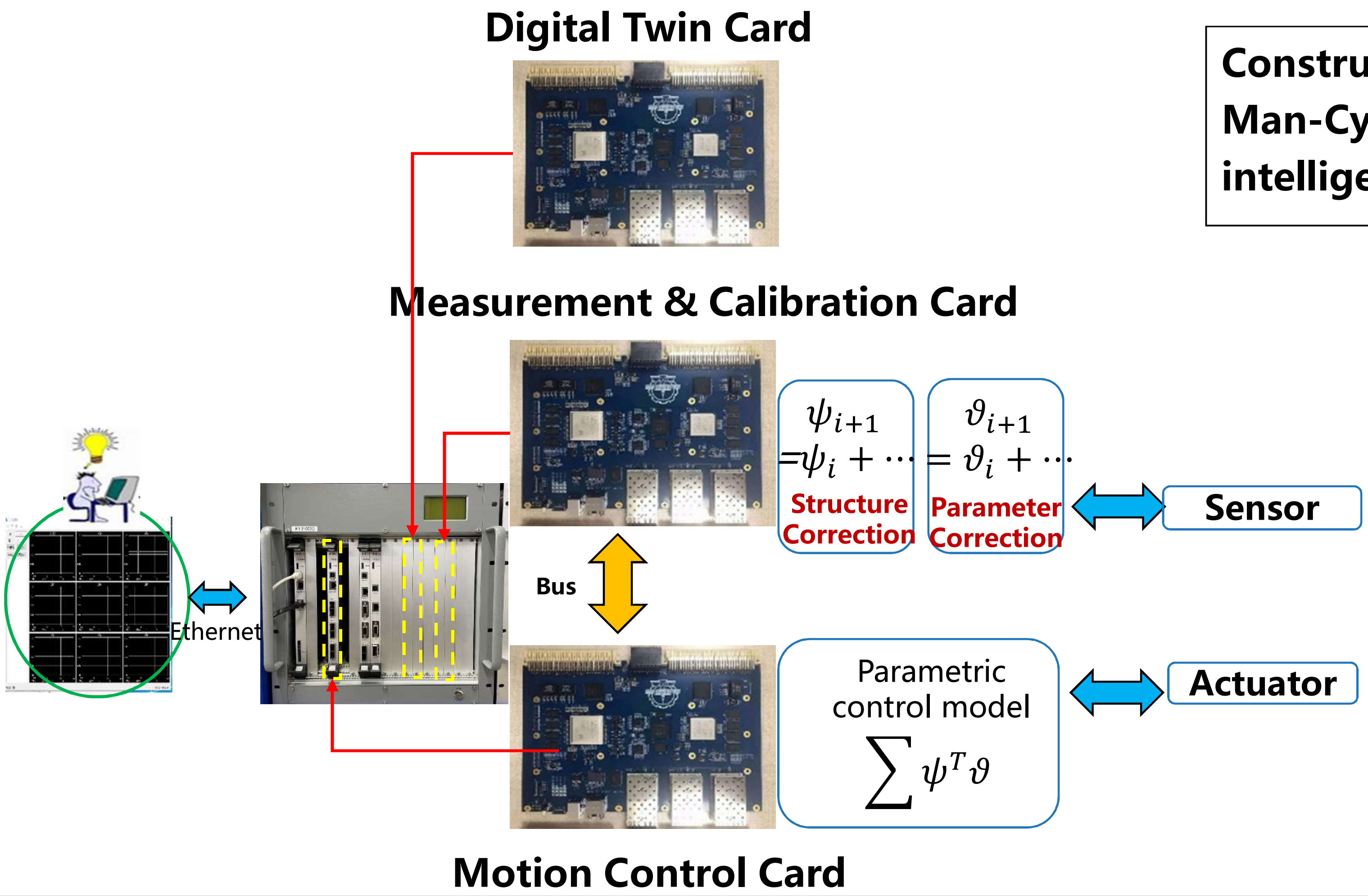
4. Asymmetric S-curve Planning

Results & discussions





5. Conclusion and Outlook



Construct a Man-Cyber-Physical intelligent control system

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Thank You!