1. Iterative learning control

**Respect the repetitive.**

**Time domain**

- ILC signal
- Error signal

**Iteration domain**

**Iteration 0**
- \( u^0 \)
- \( e_0 \)

**Iteration 1**
- \( u^1 \)
- \( e_1 \)
- \( Q_1 \)
- \( L_1 \)

**Iteration j**
- \( u^j \)
- \( e_j \)
- \( Q_j \)
- \( L_j \)

**Iteration j + 1**
- \( u^{j+1} \)
- \( e_{j+1} \)
- \( Q_{j+1} \)
- \( L_{j+1} \)

**Optimization in frequency domain (convex optimization)**

**Contributions:**
1. A **systematic design framework** for arbitrary-order ILC (a theorem).
2. Optimal learning filters in the sense of \( \mathcal{H}_\infty \) norm (convex optimization).
3. Design approach in iteration-frequency domain.
4. High-order ILC design with explicitly considering system variations - promising in robotic systems, etc.
5. Include high-order ILC and ILC with current feedback into one framework for optimization

2. Main contribution: a systematic design methodology and a theorem

**Theorem:**
With certain assumptions, the above \( N \)-th order ILC design problem is equivalent to the following problem: design a ‘feedback controller’ \( L_\infty \) for the ‘plant’ \( M \) such that the \( \mathcal{H}_\infty \) norm of the following ‘closed-loop’ system from \( z \) to \( w \) \((T_{zw})\) is minimized.

\[
\begin{bmatrix}
0_{N-1,1} & I_{N-1,N-1} \\
0_{N-1,1} & 0_{N-1,1}
\end{bmatrix}
\]

From high-order ILC to \( \mathcal{H}_\infty \) optimal control problem

\[
W = \text{diag}(W_1, W_2, \ldots, W_N)
\]

3. Application to high-precision wafer scanning system

- Counter-mass
- Reticle stage
- Wafer stage
- Laser interferometer

**Figure** Wafer scanning system

- Learning filters in time domain
- Tracking error in iteration domain
- Tracking error in time domain

**Figure** Experimental validation of wafer scanning systems

4. Application to industrial manipulator (explicitly considering system variations)

- **H-infinity based ILC:** failed
- **\( \mu \)-based ILC:** succeeded

**Convergence rate: much slower**

**Position error consistently decreases!**

*Collaborated with Dr. Cong Wang (now Professor at NJIT)*