Distributed Iterative Learning Control for a Team of Quadrotors

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Motivation

time delays!

disturbances!

model mismatches!

Learning can make multi-robot coordination more accurate or faster, and enable it to adapt to changing tasks or environment!

Distributed ILC for a Team of Quadrotors

Distributed Control:

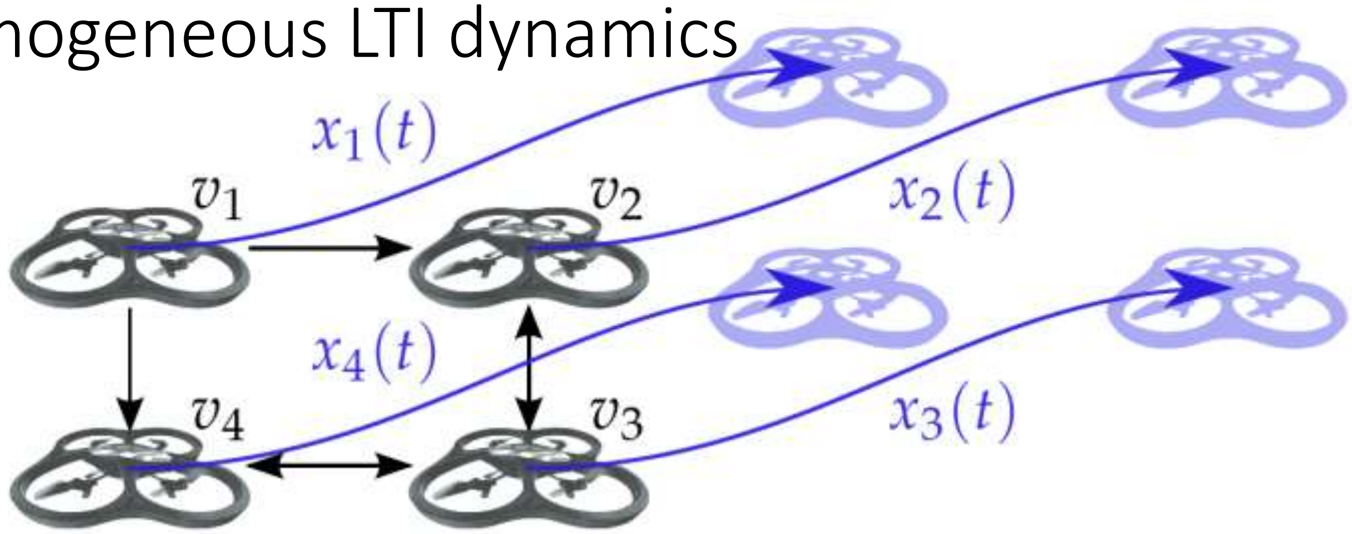
- No central control unit
- Autonomous agents
- Communication only between certain neighbors

Iterative Learning Control (ILC):

- Machine Learning technique
- Learning by repetition
- Updating the feedforward input based on past measurements

Team of Quadrotors:

- Goal: synchronous formation flying
- Homogeneous LTI dynamics



Problem Formulation

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Related Work

There exist several studies on…

- ILC for a **single** agent:
  - theoretic survey *[Bristow, 2006]*
  - quadrotor vehicle *[Schoellig, 2012]*
- **multi-agent** ILC: *[Ahn, 2009; Meng, 2012; Yang, 2012]*

Open Problems

- previous stability proofs for multi-agent ILC restricted to D-type learning functions
  => *cannot compensate for position offsets*
- pure feedforward control
  => *cannot compensate for non-repetitive errors*
- no experimental validation so far

theoretical development of advanced ILC algorithms
for multi-agent systems (MAS) & experimental implementation

Distributed ILC for MAS – Algorithm

Idea of ILC :

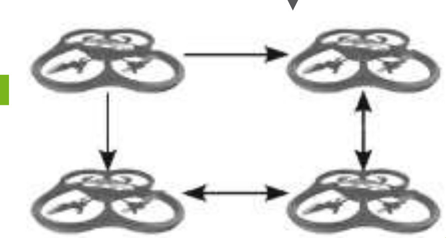
Use error information to improve feedforward input for subsequent iterations!

New Input = Old Input + Correcting Action, depending on error in last trial

[Arimoto, 1984]

$$e = y_{des} - y$$

[Ahn, 2009]



$$e_i = \sum_{j=1}^{N} a_{ij}(y_j - y_i) + b_i(y_{des} - y_i)$$

Goal: synchronous reference tracking

so far input update for multi-agent ILC only based on error derivative

- restrictive, limited design parameters
- position offsets can not be compensated

$$u_{i,k+1} = u_{i,k} + \mathrm{L} \cdot e_{i,k}$$

agent i, *iteration k*

where **L** can be an arbitrary linear mapping in discrete time!

Distributed ILC for MAS – Proof of Stability

Lifted System Representation

[Bristow, 2006]

- ILC stability analysis in discrete time
- time samples => full trajectory vectors

Graph Theoretical Definitions

[Yang, 2012]

- Concept of graph Laplacian $\mathcal{L}_\mathcal{G}$
- Reference as virtual leader node => $\mathcal{B}$
- Single agents' states => full MAS state

System Dynamics P, Learning Function L, w/ diagonal entries $p_1,\, l_0 \in \mathbb{R}$

Graph Information $(\mathcal{L}_\mathcal{G} + \mathcal{B})$ with eigenvalues λ_i

Theorem 1:

The multi-agent ILC is **asymptotically stable** if and only if

$$\rho\big(\mathrm{I} - (\mathcal{L}_\mathcal{G} + \mathcal{B}) \otimes \mathrm{LP}\big) < 1.$$

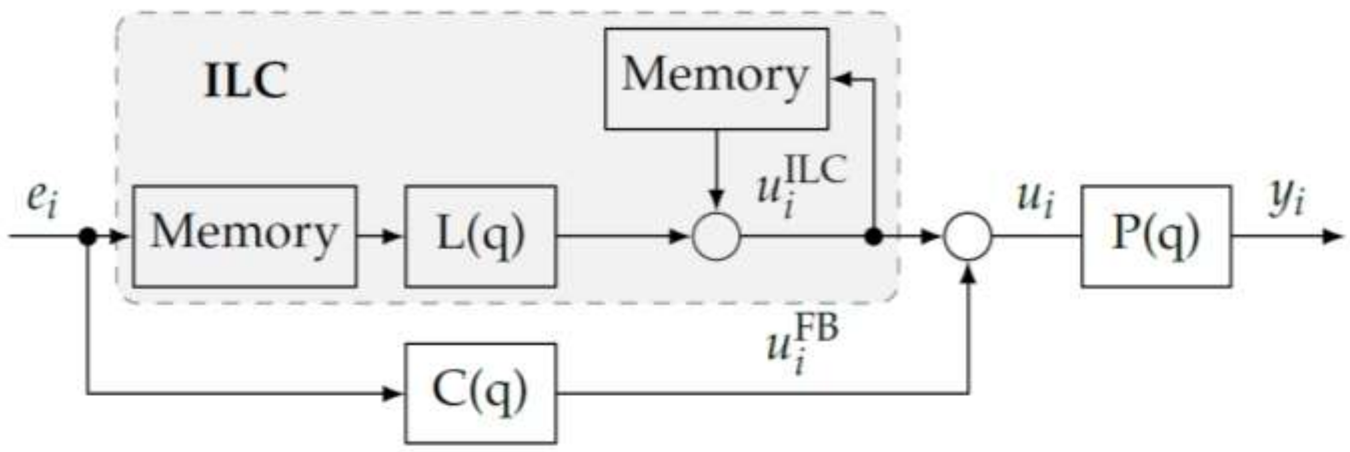
For causal learning, this holds iff

$$\max_i |1 - \lambda_i l_0 p_1| < 1.$$

crucial design parameter

Distributed ILC for MAS –
Combination with Consensus Feedback Control

ILC with Feedback



Theorem 2:

A time domain feedback term

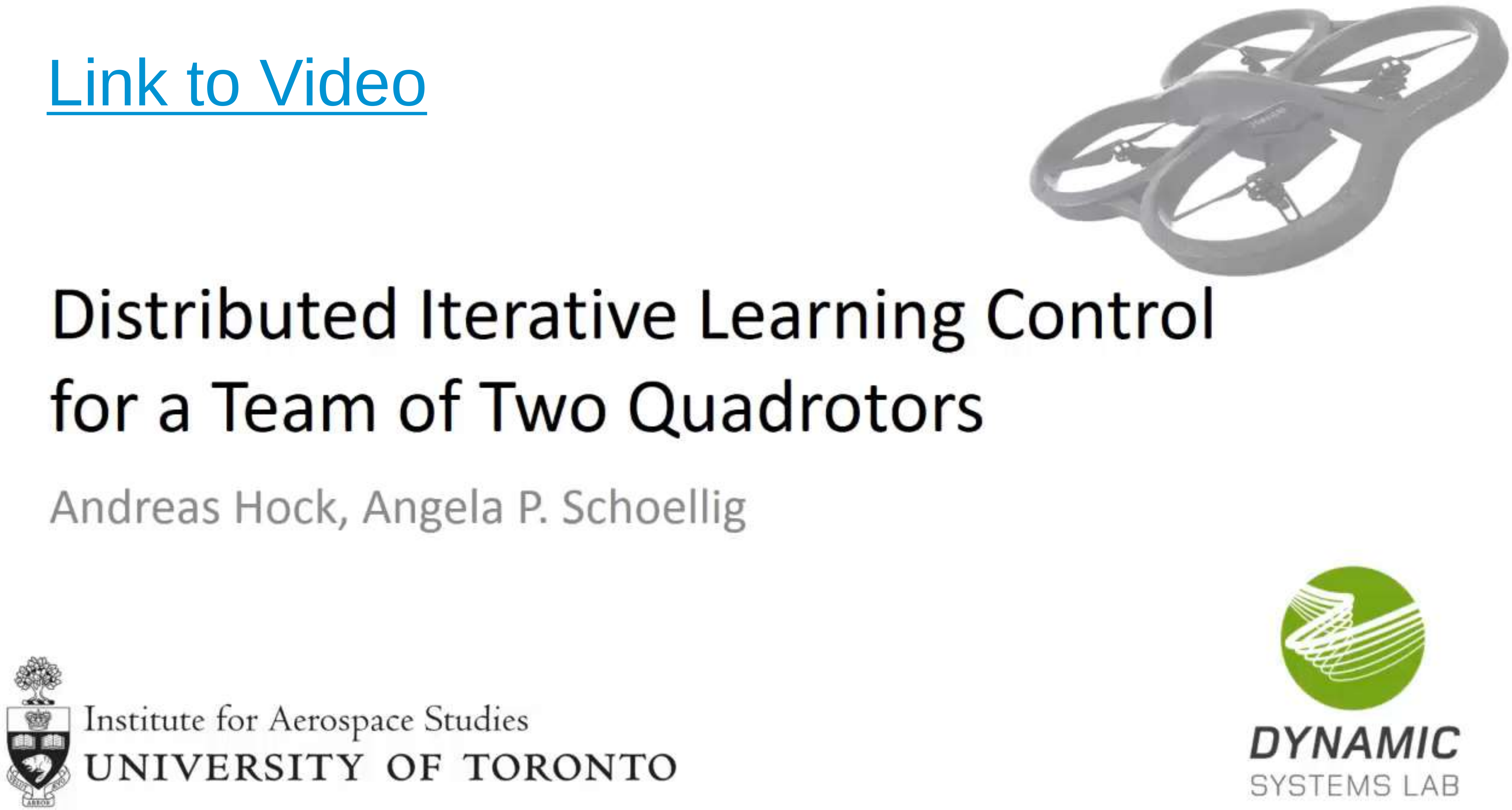
$$u_i^{\mathrm{FB}} = \mathrm{C} \cdot e_i,$$

with linear mapping **C** , does not affect stability of the proposed ILC system!

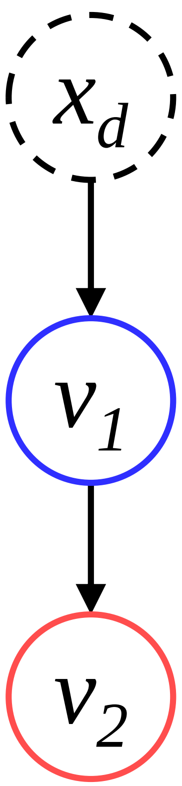
NEW!

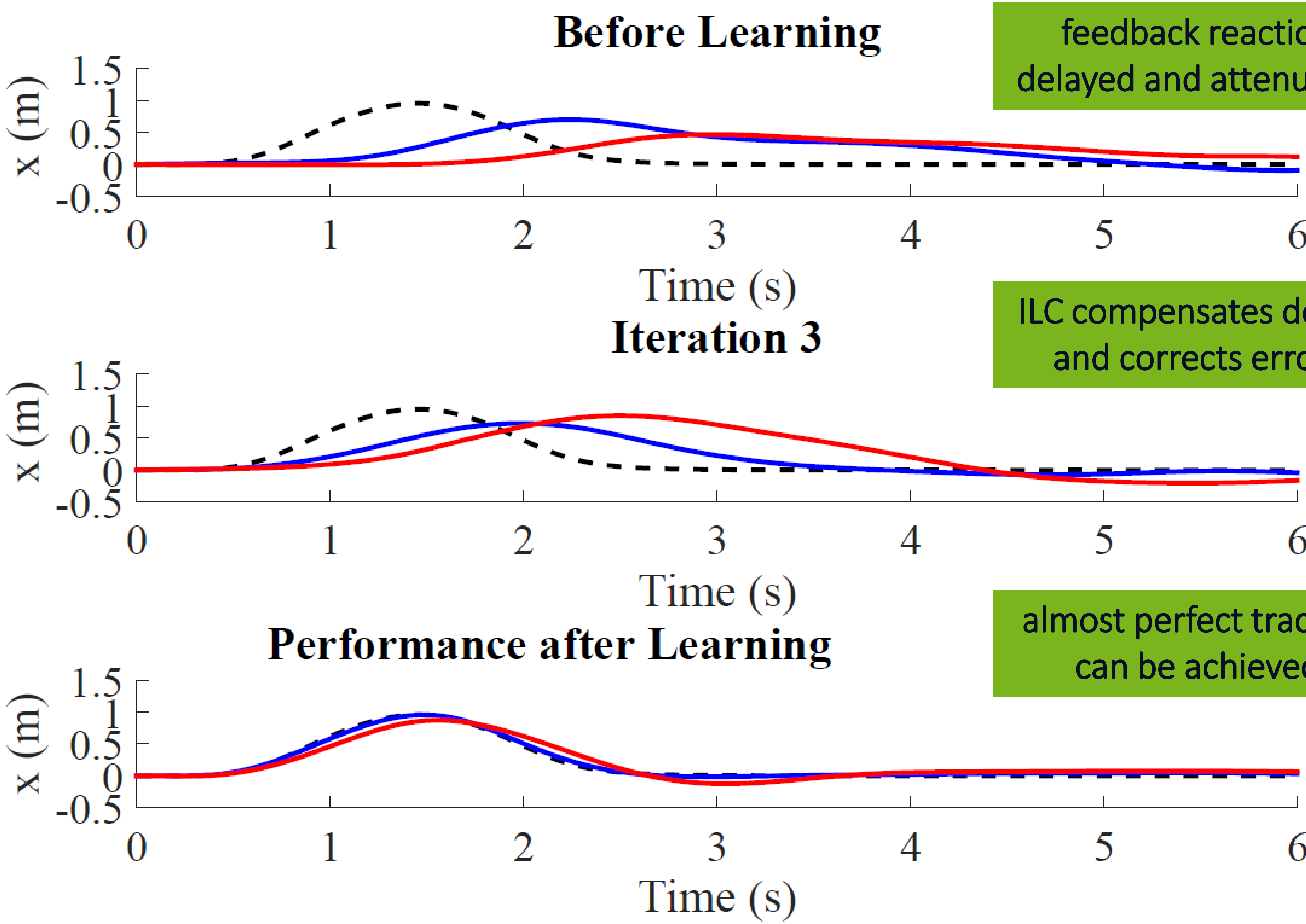
COMPARISON	Feedback Control (Consensus)	ILC	ILC + Consensus Feedback
*learn from **tracking errors***	✗	✓	✓
*compensate for **non-repetitive errors***	✓	✗	✓
*incorporate **repetitive disturbances***	✗	✓	✓

Link to Video



Experimental Results -
Trajectories in x over time



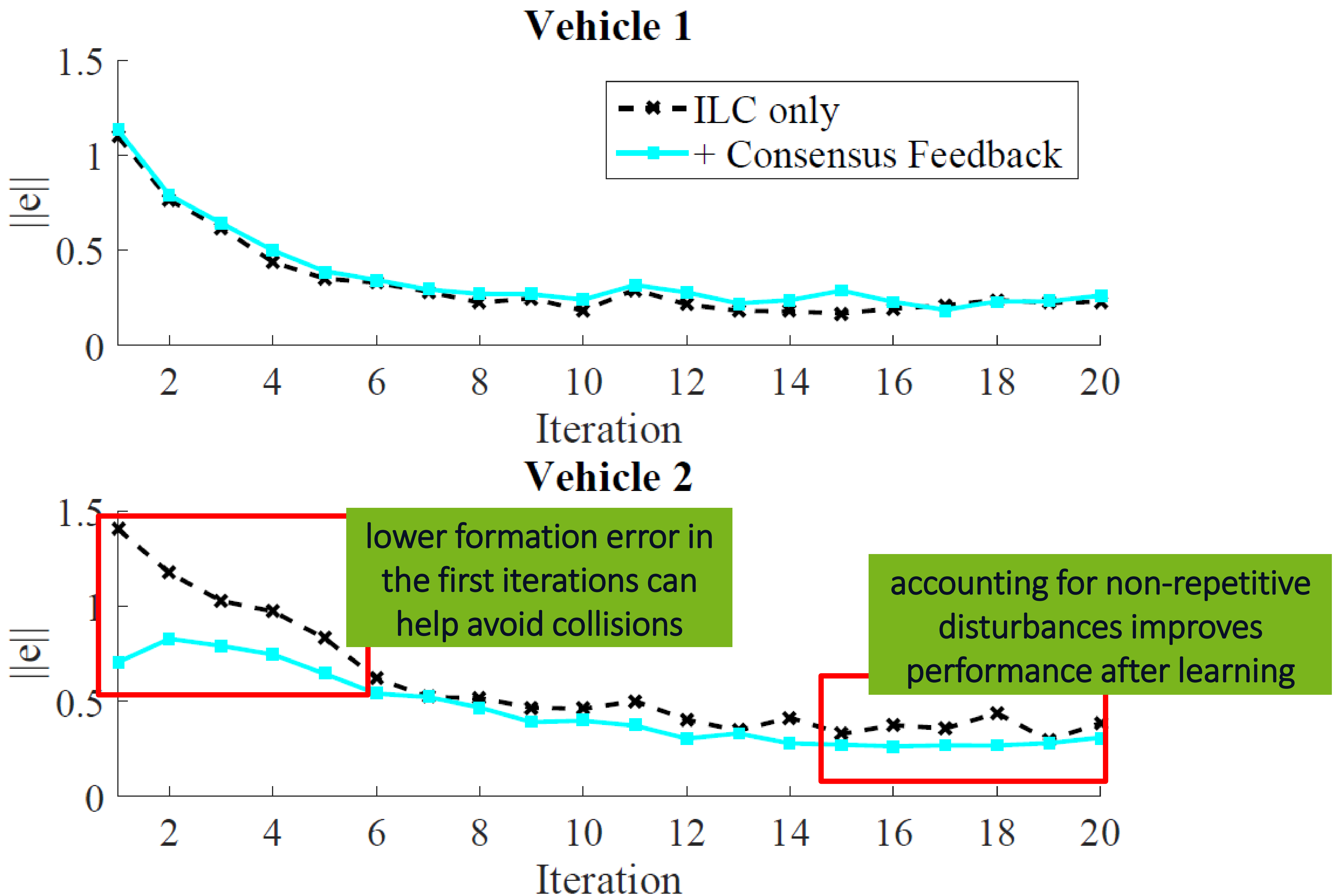


feedback reaction delayed and attenuated

ILC compensates delays and corrects errors

almost perfect tracking can be achieved

Experimental Results -
Error Convergence Comparison



Conclusion

- **Generalized stability proof** demonstrated that the multi-agent ILC algorithm converges if l_0 is chosen properly => many tuning options for input-update rule
- We proved that including a **consensus feedback controller** does not affect stability but improves performance as it compensates for non-repeating disturbances
- Multi-agent ILC was successfully implemented on a **real experiment** for the first time

Link to Video

Distributed Iterative Learning Control for a Team of Four Quadrotors

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Thank you!

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