Cooperative Passivity-Based Control for End-Effector Synchronisation

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Delft University of Technology

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Outline

- Introduction
- Passivity
- Cooperative r-Passivity-Based Control
- Experimental Results
- Conclusions

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Introduction

Our Objective

Synchronise end-effectors of mechanical systems in general environments.

Our Objective

Introduction

Passivity

Cooperative rPBC

Experimental Results

Conclusions

Synchronise end-effectors of mechanical systems in general environments.

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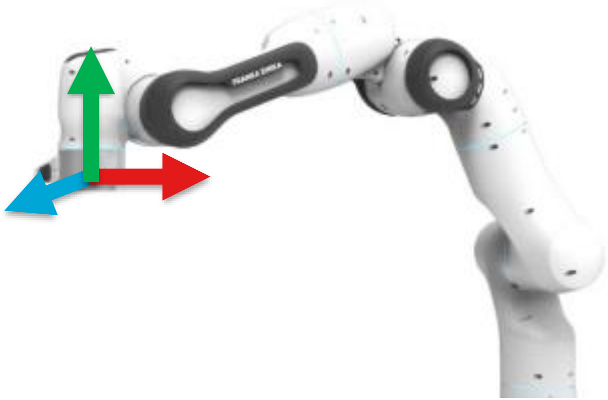
Our Objective

Synchronise end-effectors of mechanical systems in general environments.

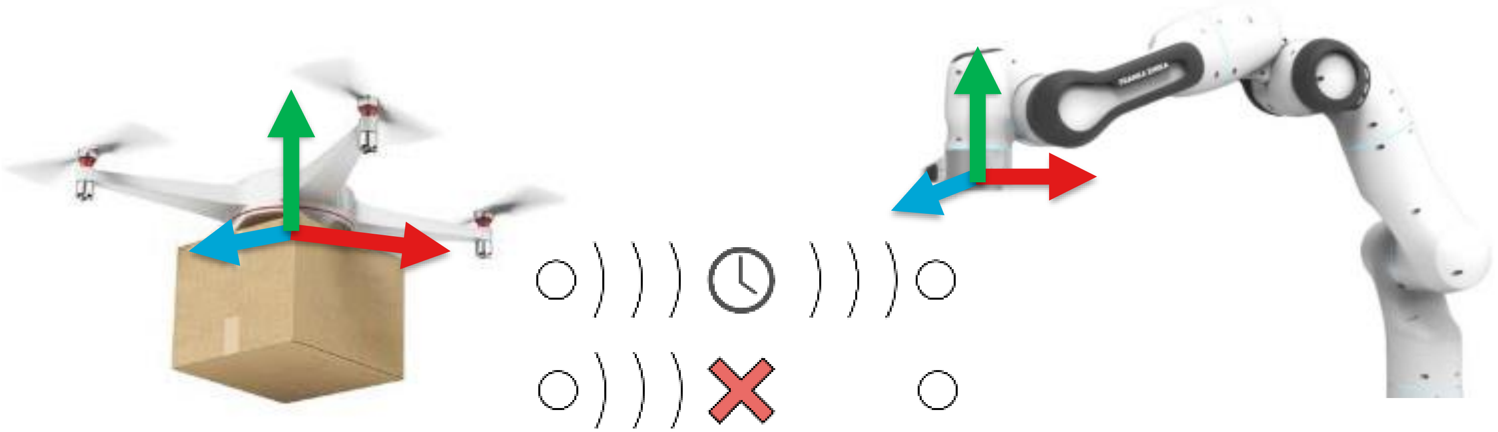


Possible applications

- Sort and packing problems
- Multi-vehicle package delivery
- Autonomous platoons
- Spacecraft alignment
- …

Our Objective

Synchronise end-effectors of mechanical systems in general environments.



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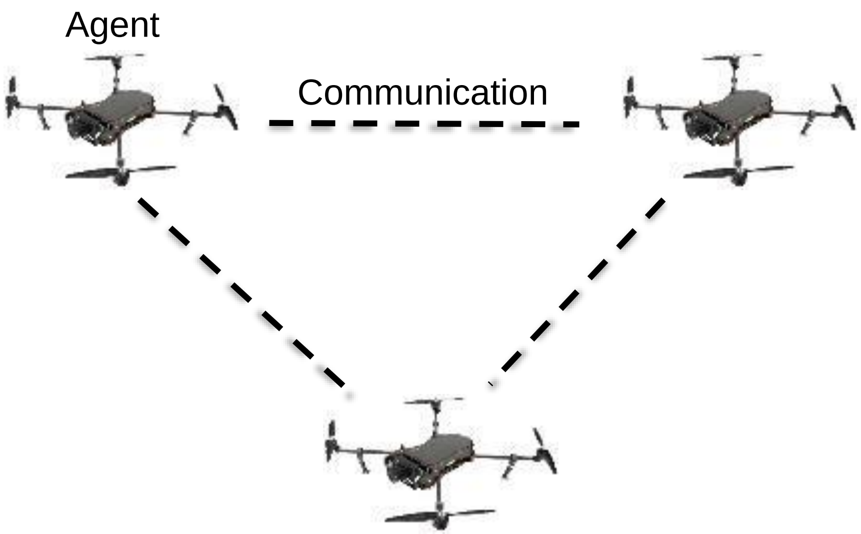
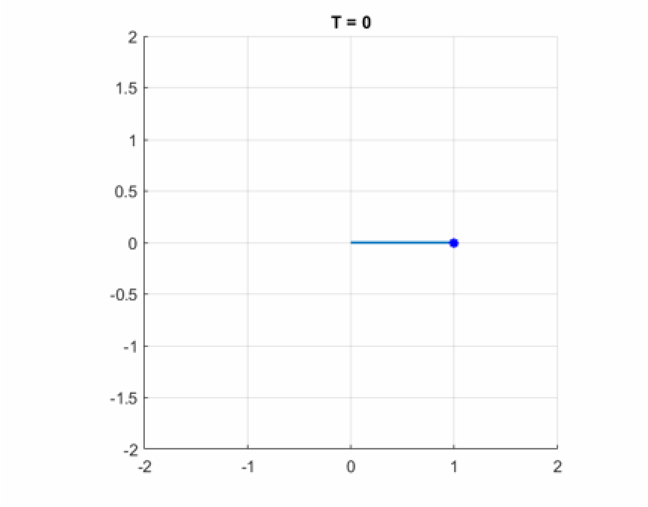
The approach

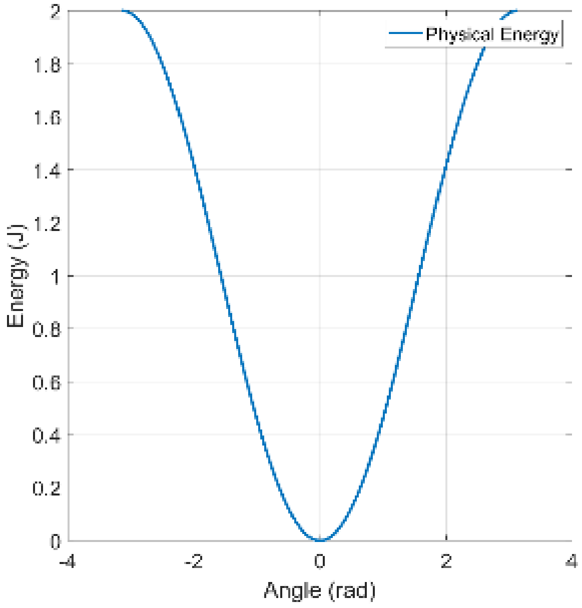
Cooperative Passivity-Based Control



The approach

Cooperative Passivity-Based Control





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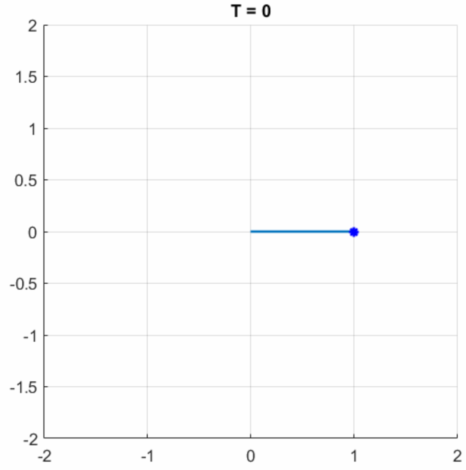
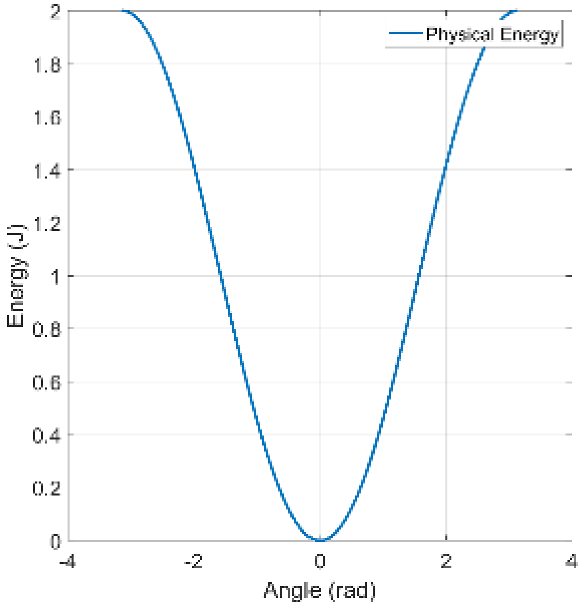
The approach

Cooperative Passivity-Based Control





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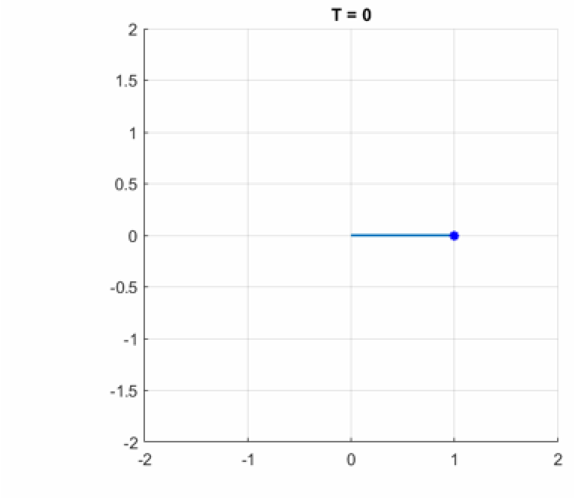
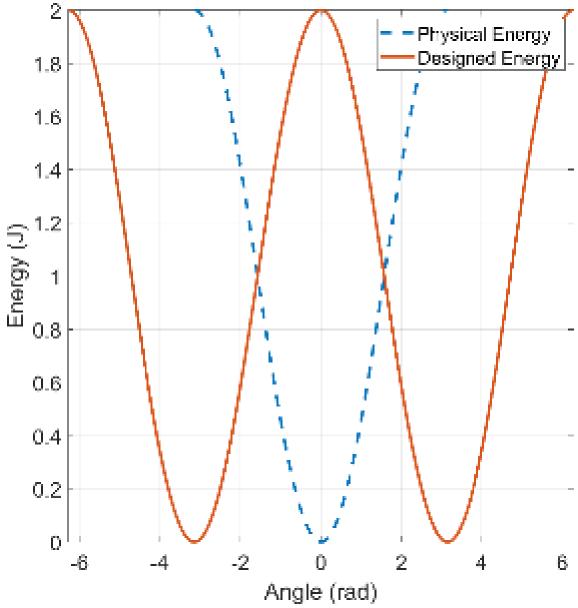
The approach

Problem Definition
IDA-PBC
Network Scheme
Agent Scheme
Simulation Results

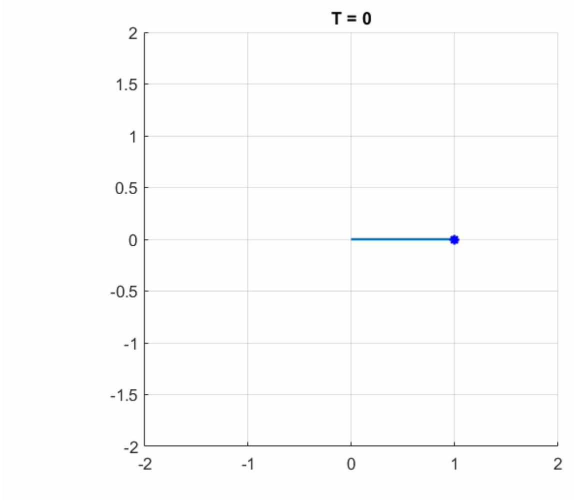
Cooperative Passivity-Based Control

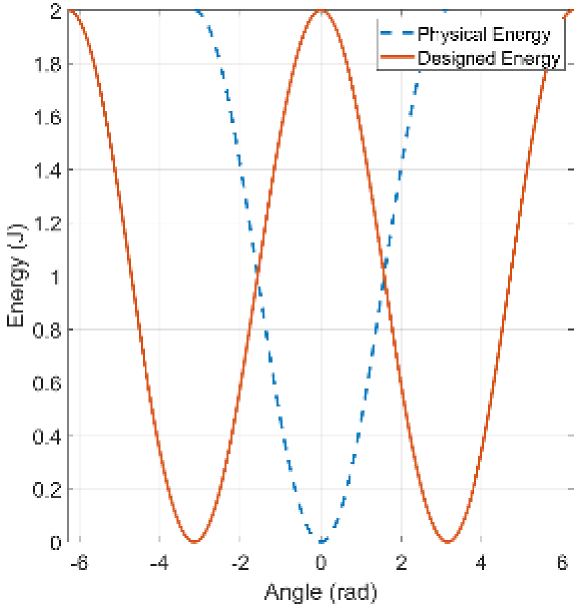




The approach

Cooperative Passivity-Based Control





The approach

Cooperative Passivity-Based Control

- Zero energy → Control objective

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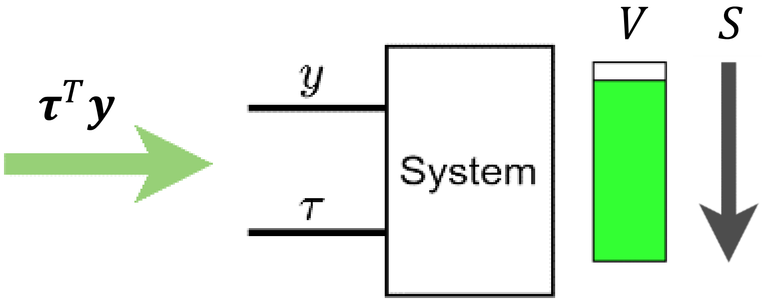
Passivity

Notion of Passivity

Supplied energy is either *stored* or *dissipated*

$$\dot{V} + S = \boldsymbol{\tau}^T \boldsymbol{y}$$



Cooperative Control

- No energy supply

  $\dot{V} = -S \leq 0$ (Lyapunov)

Cooperative Control

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Cooperative Control

Introduction

Passivity

Cooperative rPBC

Experimental Results

Conclusions

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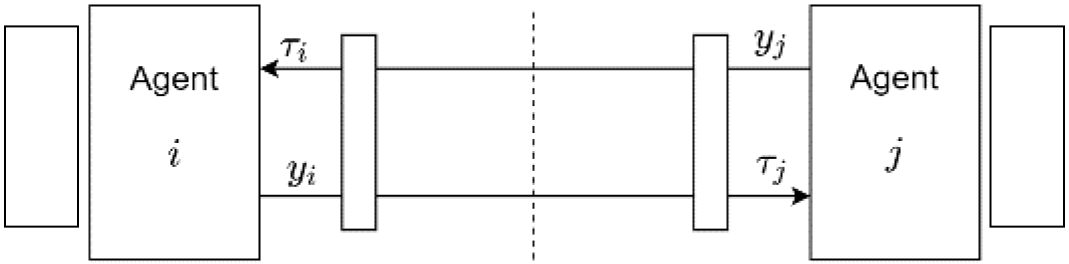

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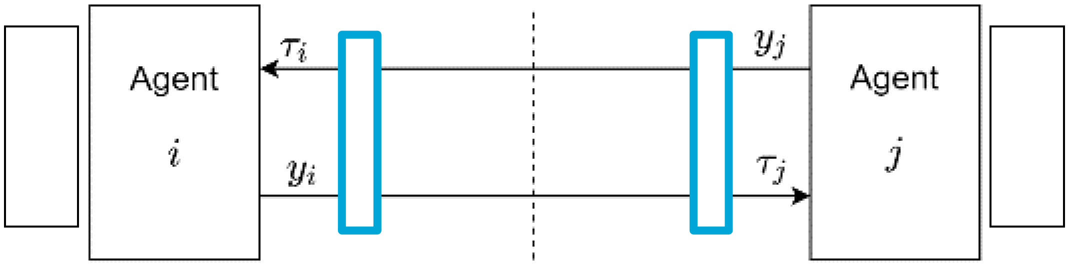
Cooperative Control

- No energy supply

  $\dot{V} = -S \leq 0$ (Lyapunov)

- Zero energy → Cooperative control objective



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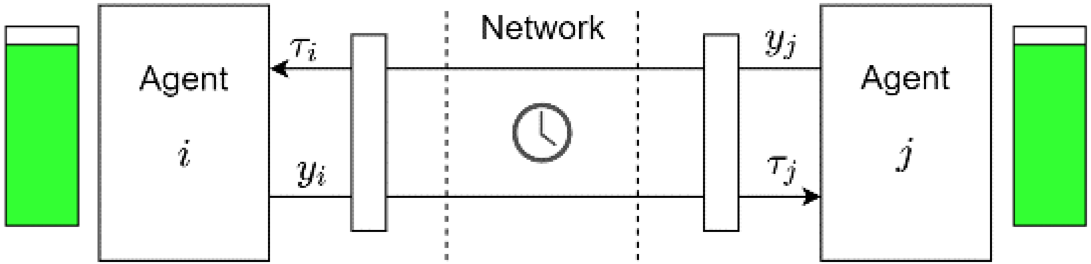
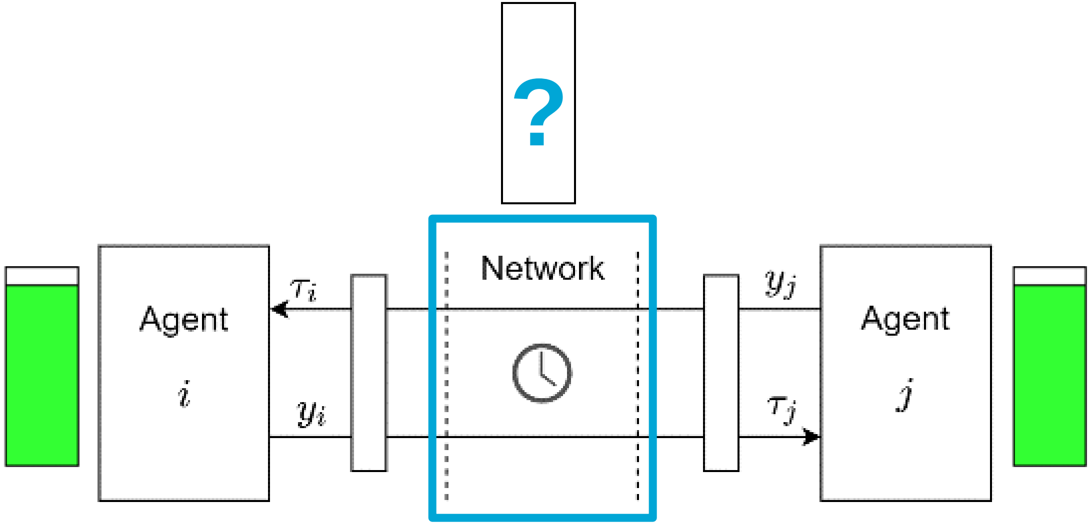
PBC with Delays

- What if delays are present?



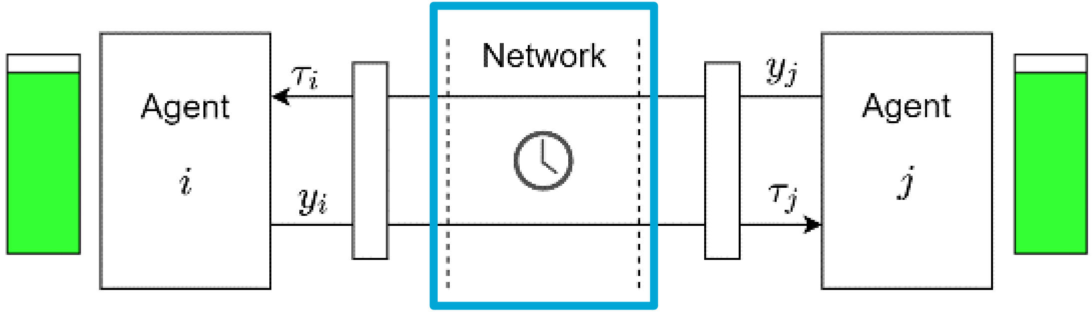
PBC with Delays

- No description of the energy in the network.



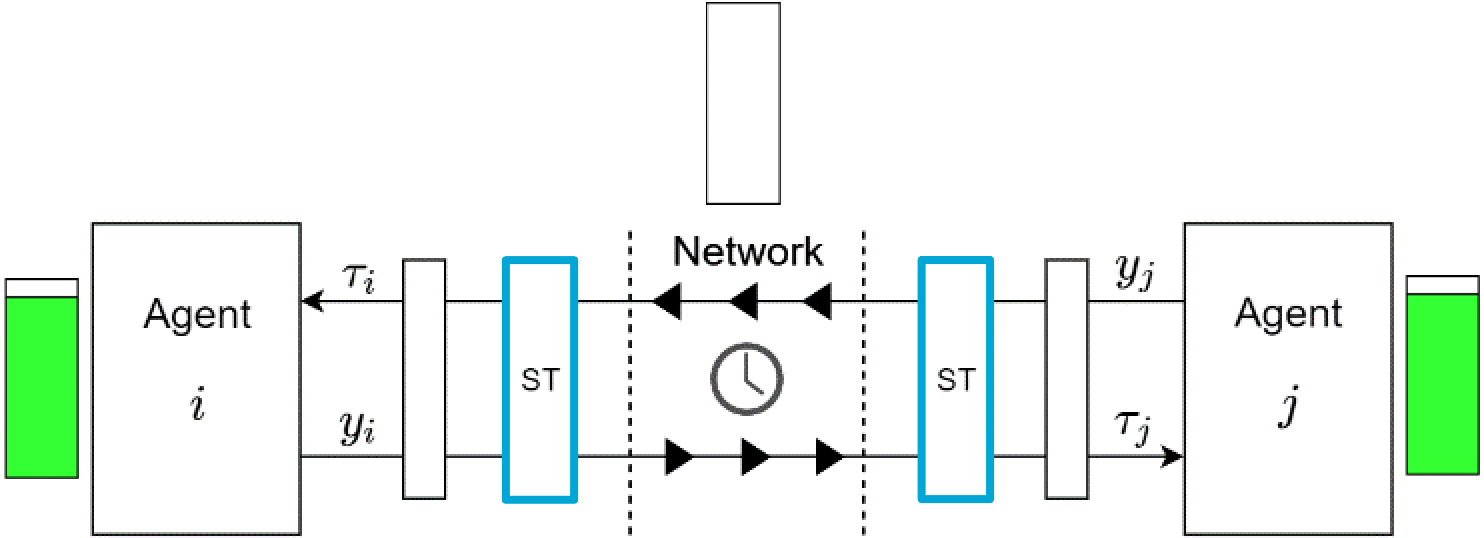
PBC with Delays

- No description of the energy in the network.
- **Solution:** Convert network signals to energy packages



Scattering Transformation

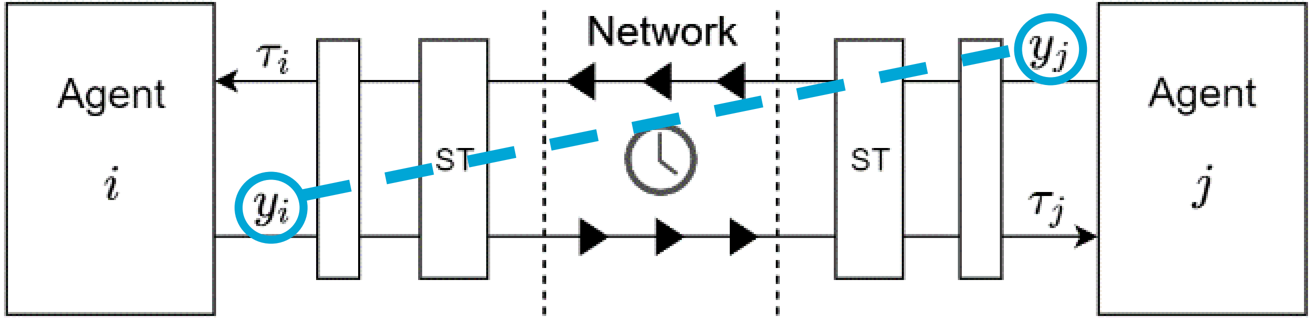
- Convert network signals to energy packages using the Scattering Transformation (ST)



PBC with Delays

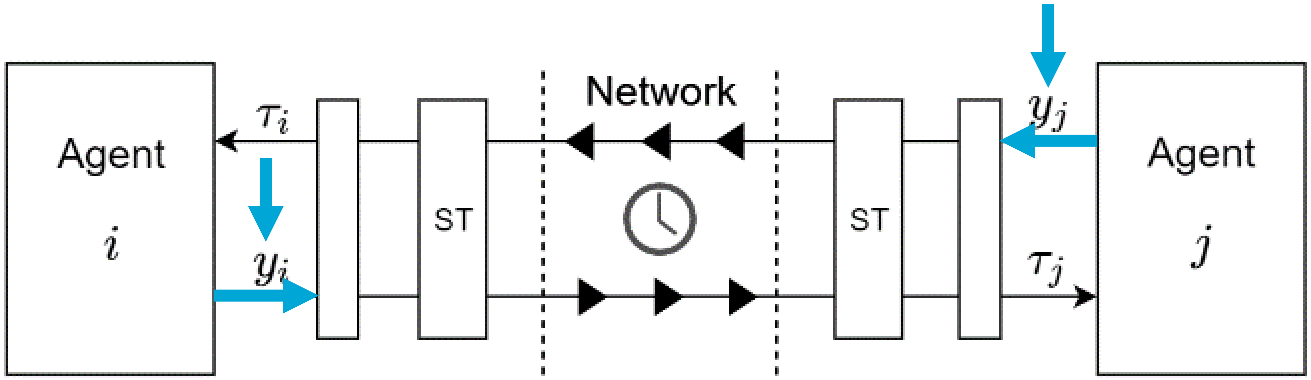
- Output synchronization:

$$\lim_{t\to\infty} \boldsymbol{y}_{\boldsymbol{j}}\left(t - T_{ji}\right) - \boldsymbol{y}_{\boldsymbol{i}} = \boldsymbol{0}$$



Cooperative r-Passivity-Based Control

Output Selection



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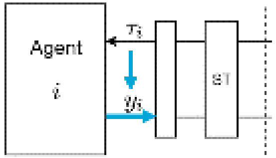
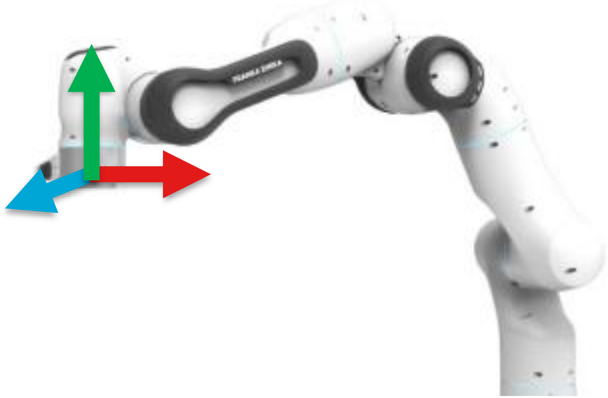


Output Selection

- Synchronisation of end-effector coordinates



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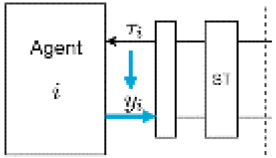
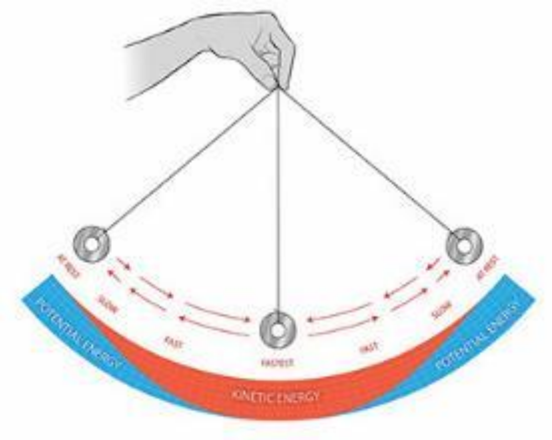


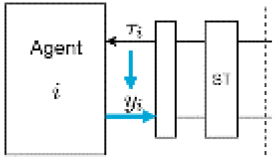
Output Selection

- Passive outputs contain velocities



Potential Energy

Kinetic Energy



Output Selection

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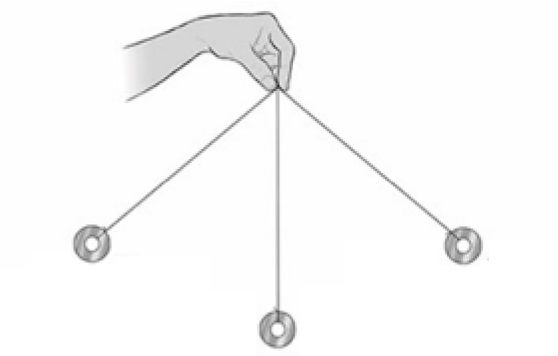

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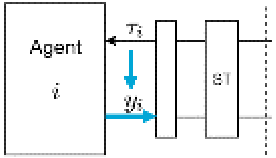
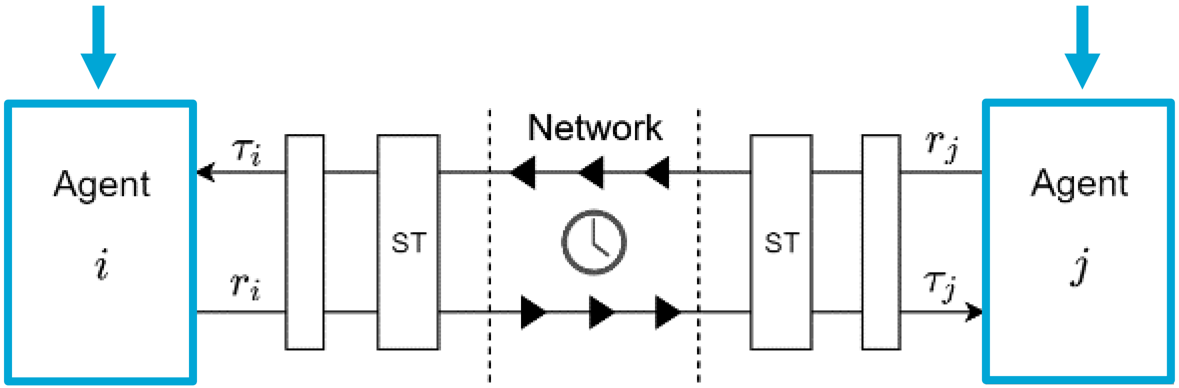


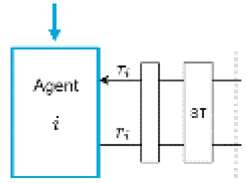
Output Selection

- Outputs
  - Fulfil our objectives with coordinates
  - Are passive with velocities

- Encode velocities and coordinates into the output $\boldsymbol{r}$
- $\boldsymbol{r} = \dot{\boldsymbol{z}} + \lambda \boldsymbol{z}$
- If $\dot{\boldsymbol{z}} \to \boldsymbol{0}$, then $\boldsymbol{r} \to \lambda \boldsymbol{z}$

r-Passive Agents



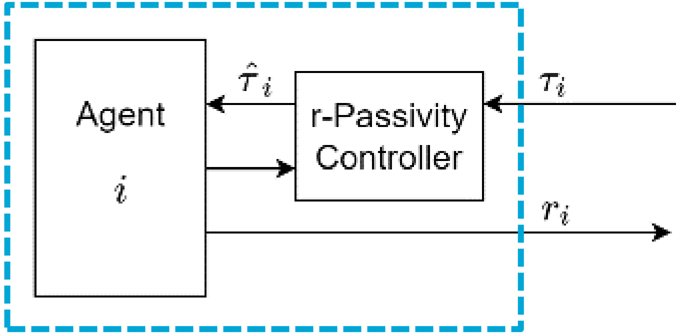


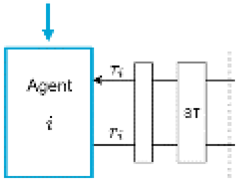
r-Passive Agents

- Introduction
- Passivity
- Cooperative rPBC
- Experimental Results
- Conclusions

- Find a control function $\hat{\boldsymbol{\tau}}_i(\boldsymbol{\tau}_i)$ such that

$$S_i = \boldsymbol{\tau}_{c,i}^T \mathbf{r}_i - \dot{V}_i \qquad \text{(r-passivity)}$$





r-Passive Agents

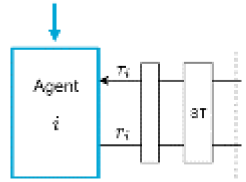
- Find a control function $\hat{\boldsymbol{\tau}}_i(\boldsymbol{\tau}_i)$ such that

$$S_i = \boldsymbol{\tau}_{c,i}^T \mathbf{r}_i - \dot{V}_i \qquad \text{(r-passivity)}$$

$$V_i = \frac{1}{2}\mathbf{r}_i^T \mathbf{r}_i + \frac{1}{2}\gamma_i \lambda \mathbf{z}_i^T \mathbf{z}_i, \qquad S_i = \gamma_i \dot{\mathbf{z}}_i^T \dot{\mathbf{z}}_i.$$

$$\downarrow$$

$$\boldsymbol{\tau}_{c,i} = \dot{\mathbf{r}}_i + \gamma_i \dot{\mathbf{z}}_i = \ddot{\mathbf{z}}_i + (\lambda + \gamma_i)\dot{\mathbf{z}}_i$$



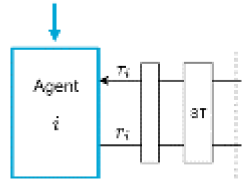
r-Passive Agents

- For fully actuated systems, solvable:

$$\boldsymbol{\tau}_i = \mathbf{M}_i \mathbf{J}_i^{\dagger} \left(\boldsymbol{\tau}_{c,i} - \mathbf{K}_{z,i} \dot{\mathbf{q}}_i \right) + \frac{\partial H_i}{\partial \mathbf{q}_i},$$

$$\mathbf{K}_{z,i} = \mathbf{J}_i \left((\lambda + \gamma_i) \mathbf{I}_{n,i} - \mathbf{M}_i^{-1} \dot{\mathbf{M}}_i \right) + \dot{\mathbf{J}}_i$$

- Dimensionality of cooperative tasks



Local Dynamics

Introduction

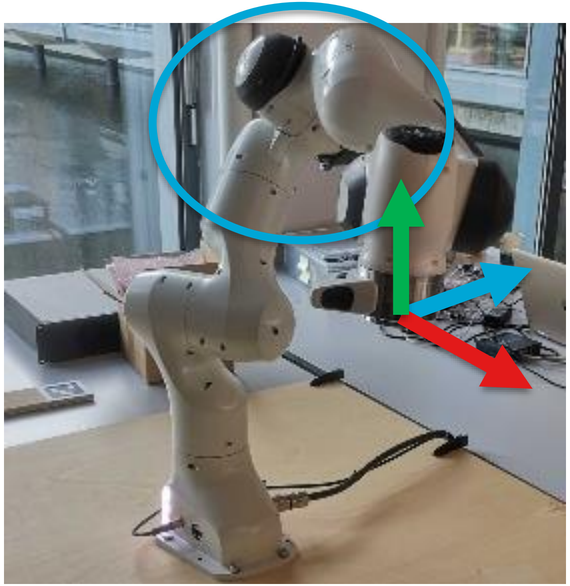
Passivity

Cooperative rPBC

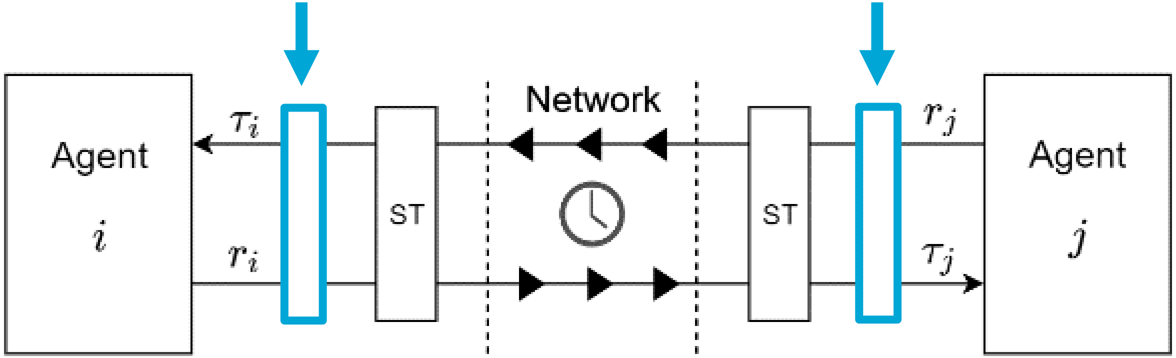
Experimental Results

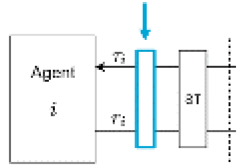
Conclusions

- Subtask optimisation



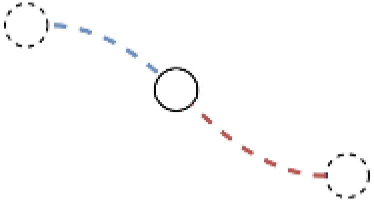
Cooperative Controls

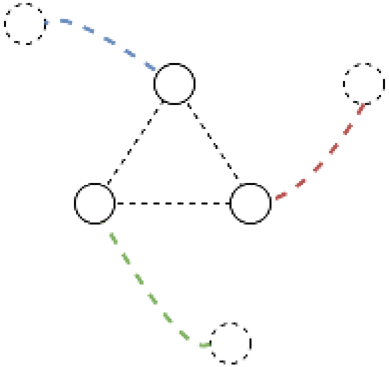




Cooperative Controls

- Gradient descend
- Objectives
  - Consensus
  - Formations
  - Leader-Follower Control





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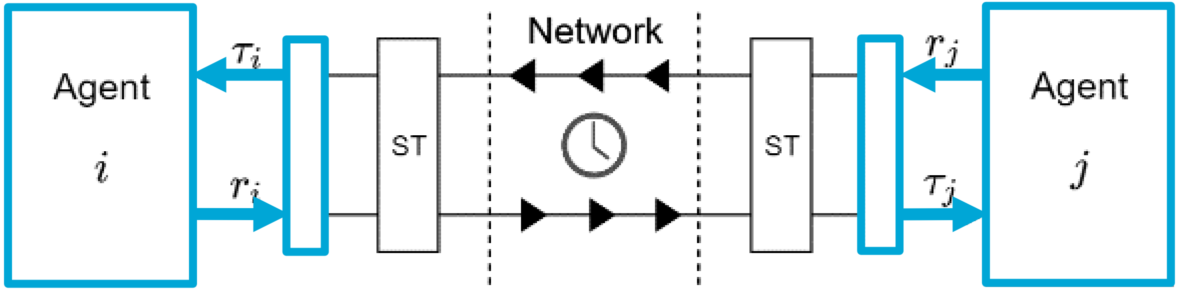
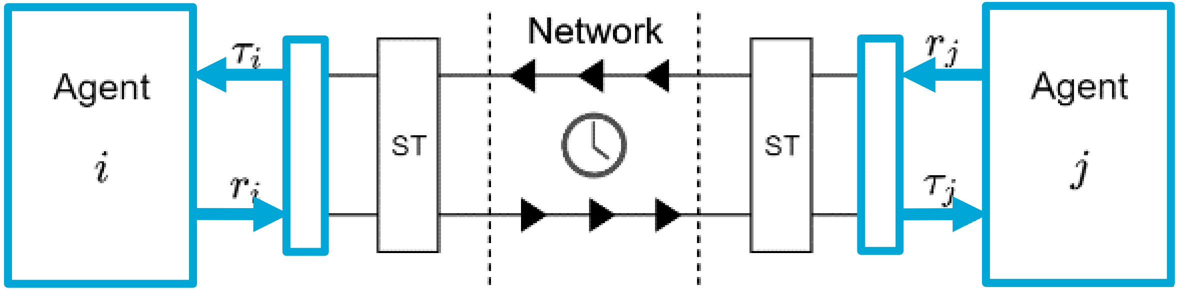
Summarizing Remarks

- We developed
  - A scheme for synchronisation with r-passive systems
  - A controller that renders agents r-passive



Summarizing Remarks

- No knowledge required of other agent dynamics
- Interconnection becomes trivial



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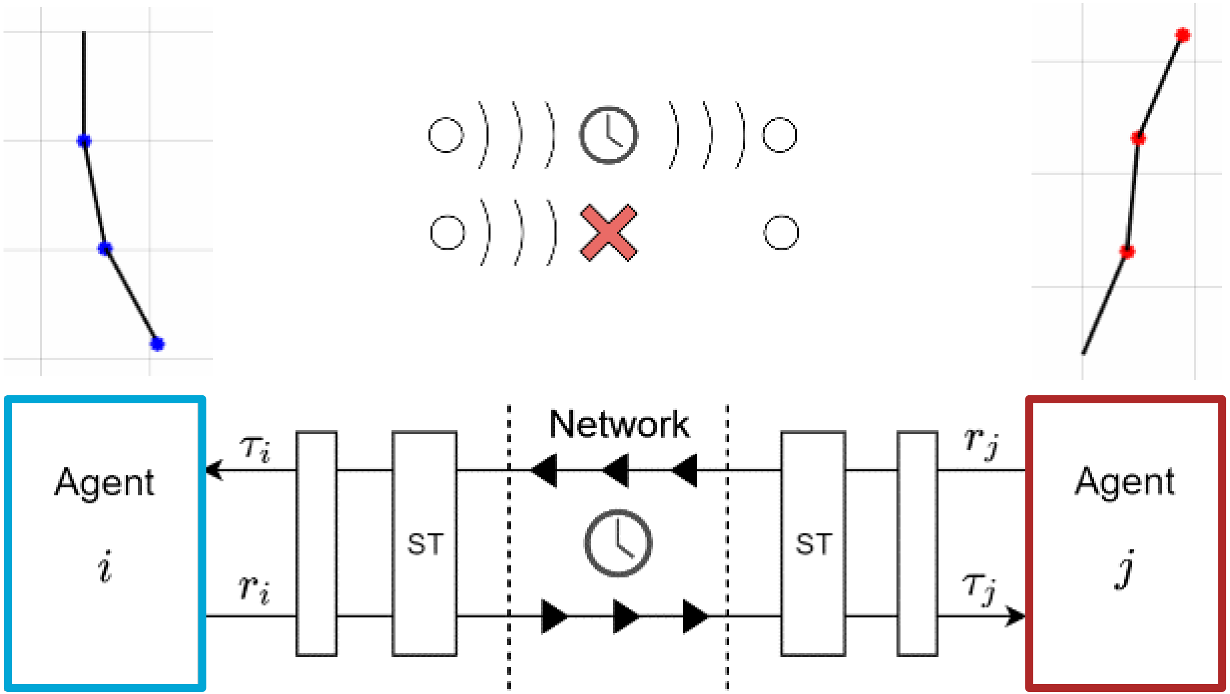
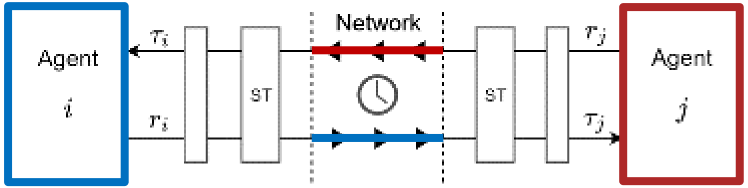
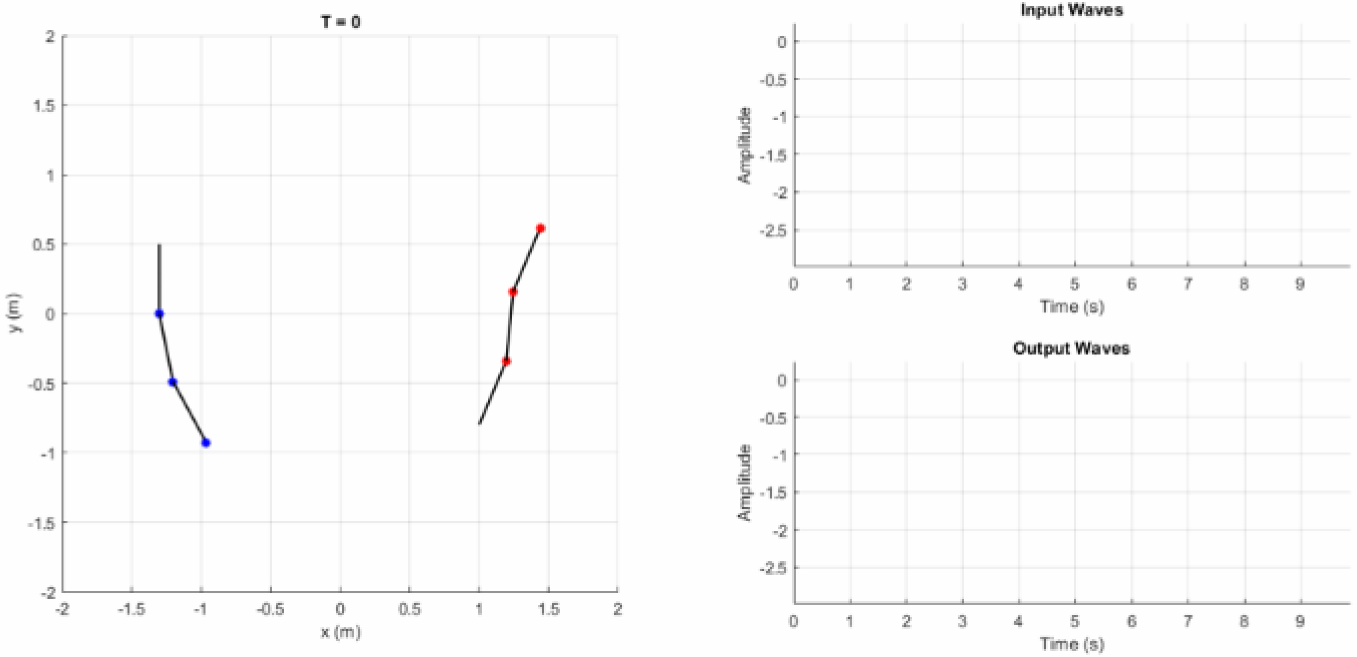
Simulation

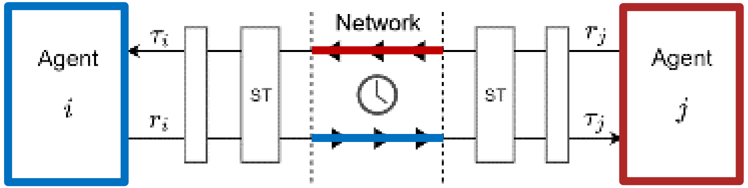


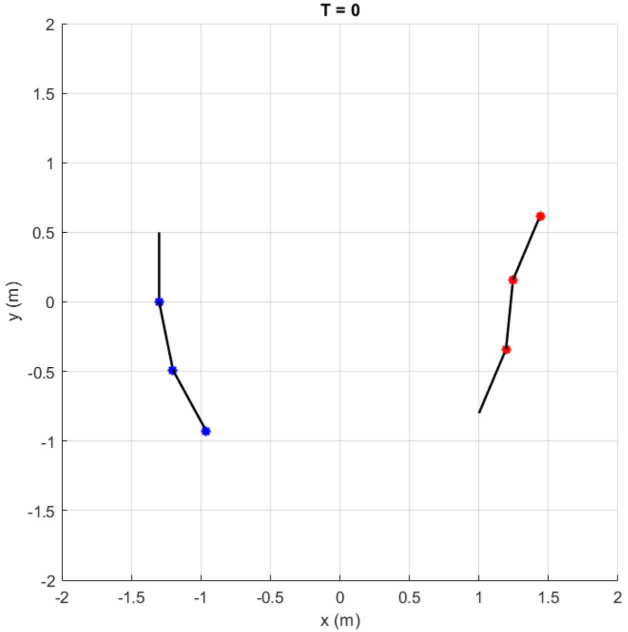


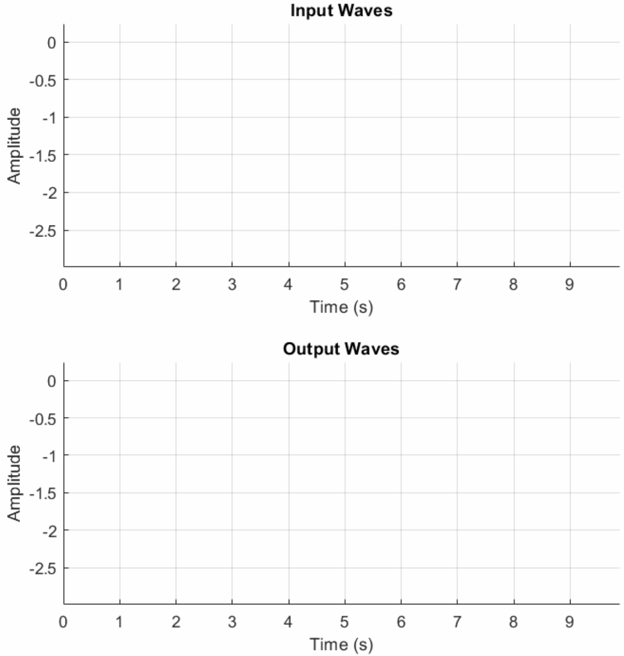
Agent
i
τ_i
r_i
ST
Network
ST
r_j
τ_j
Agent
j

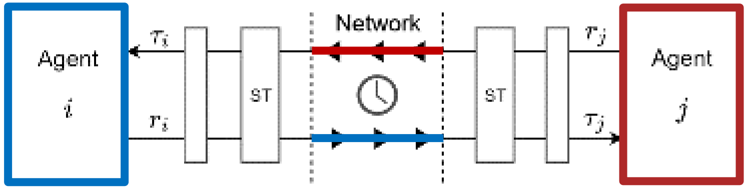


T = 0
x (m)
y (m)
Input Waves
Amplitude
Time (s)
Output Waves
Amplitude
Time (s)

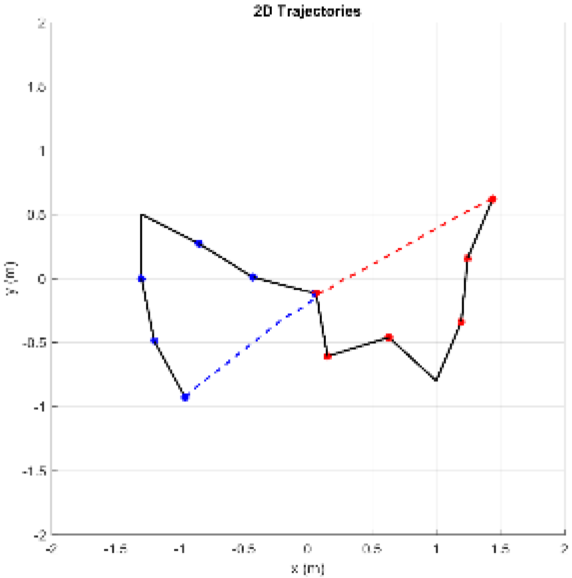

Network
Agent
i
τ_i
r_i
ST
ST
Agent
j
r_j
τ_j


T = 0
y (m)
x (m)
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2

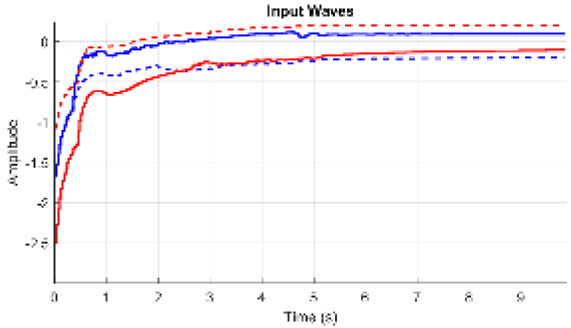

Input Waves
Amplitude
Time (s)
Output Waves
Amplitude
Time (s)
0
-0.5
-1
-1.5
-2
-2.5
0
1
2
3
4
5
6
7
8
9



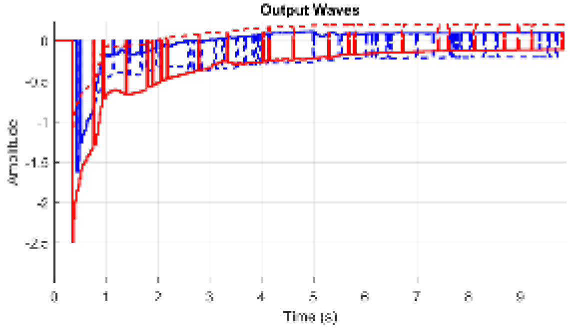
Agent
i
τ_i
r_i
ST
Network
ST
r_j
τ_j
Agent
j



2D Trajectories
y (m)
x (m)



Input Waves
Amplitude
Time (s)



Output Waves
Amplitude
Time (s)

Experimental Results

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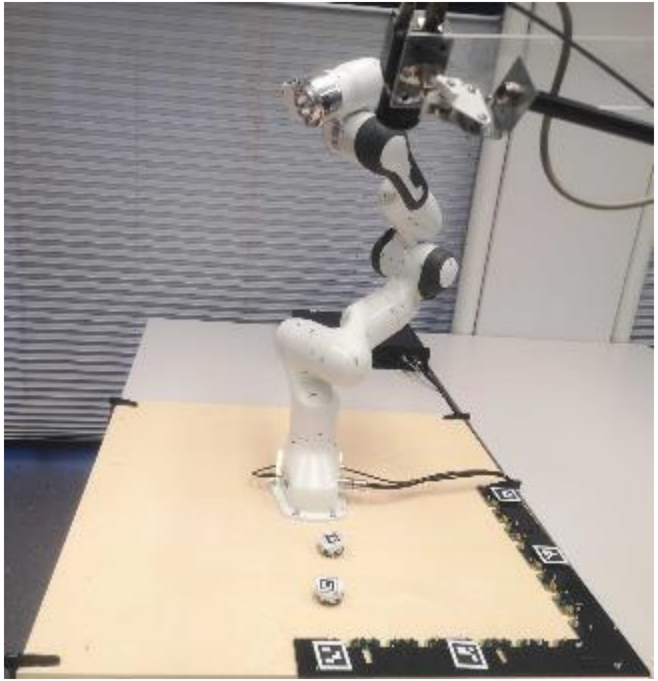
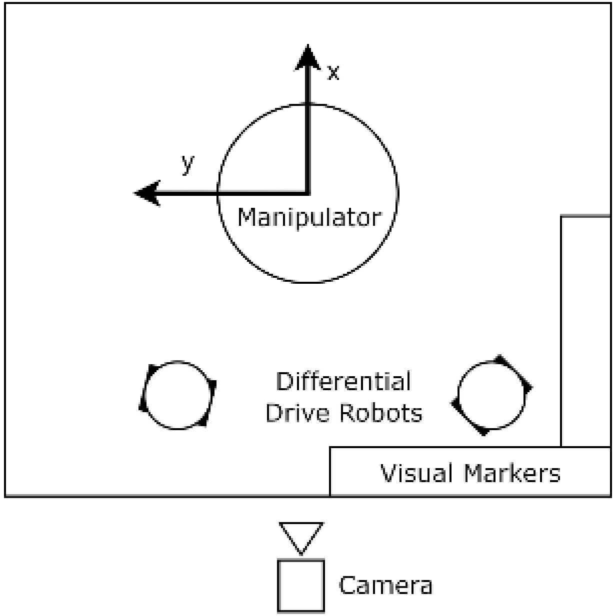
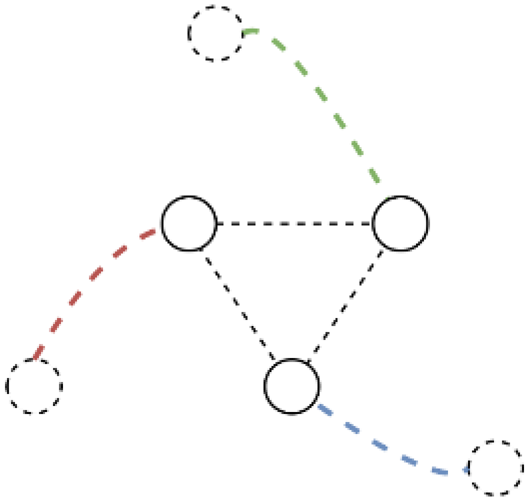
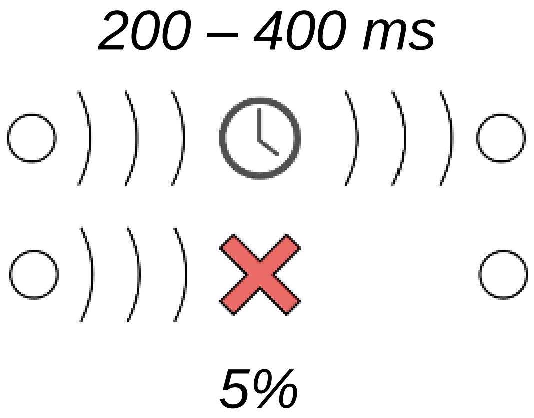
Formation Experiment



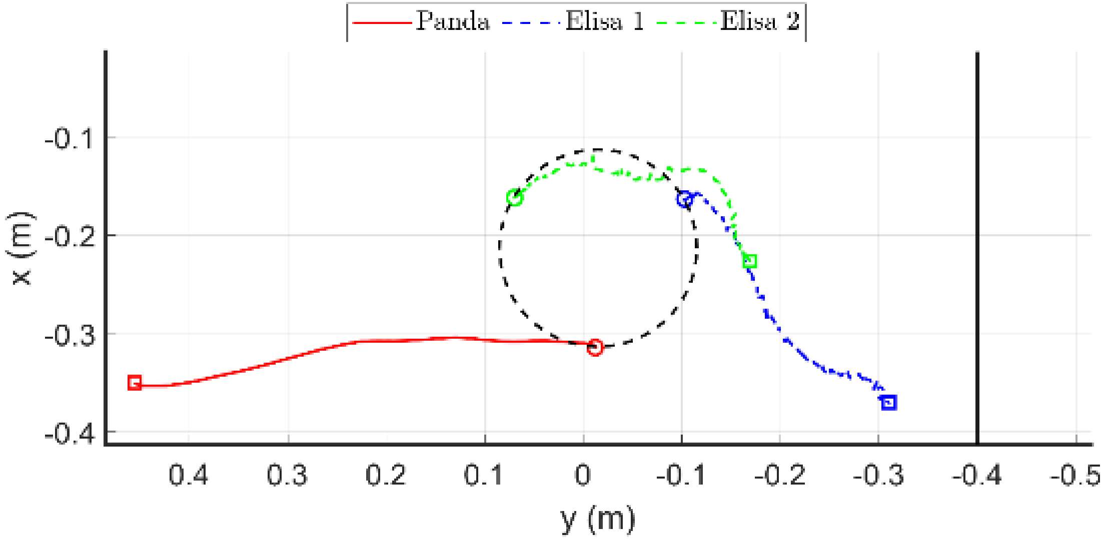


Formation Experiment





Formation Trajectories



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Conclusions

Conclusions

- We derived a cooperative controller
  - For heterogeneous, nonlinear systems
  - That does not need knowledge of other agent's dynamics;
  - For formation control with or without leaders;
  - With inherent stability in the presence of communication delays and packet loss.

Future work

- Underactuated systems
- MPC for r-passivity
- Collision avoidance

Thank you for you attention

Backup

Performance with Network Effects

- Multiple experiments
  - Delays
  - Packet loss

Introduction

Passivity

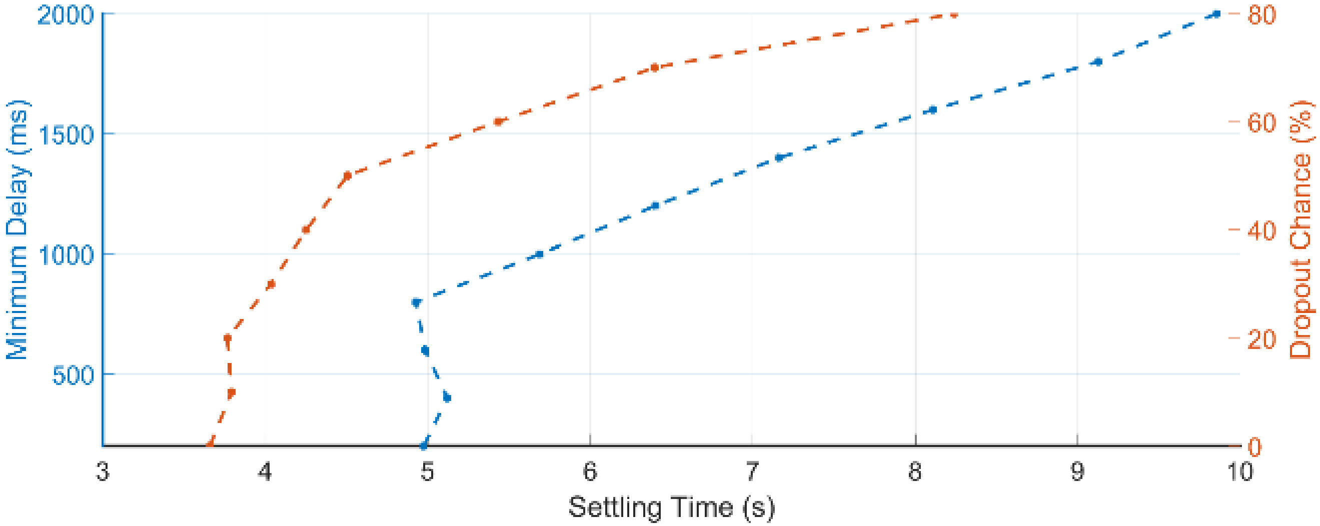
Cooperative rPBC

Experimental Results

Conclusions

Performance with Network Effects

- Multiple experiments
  - Delays



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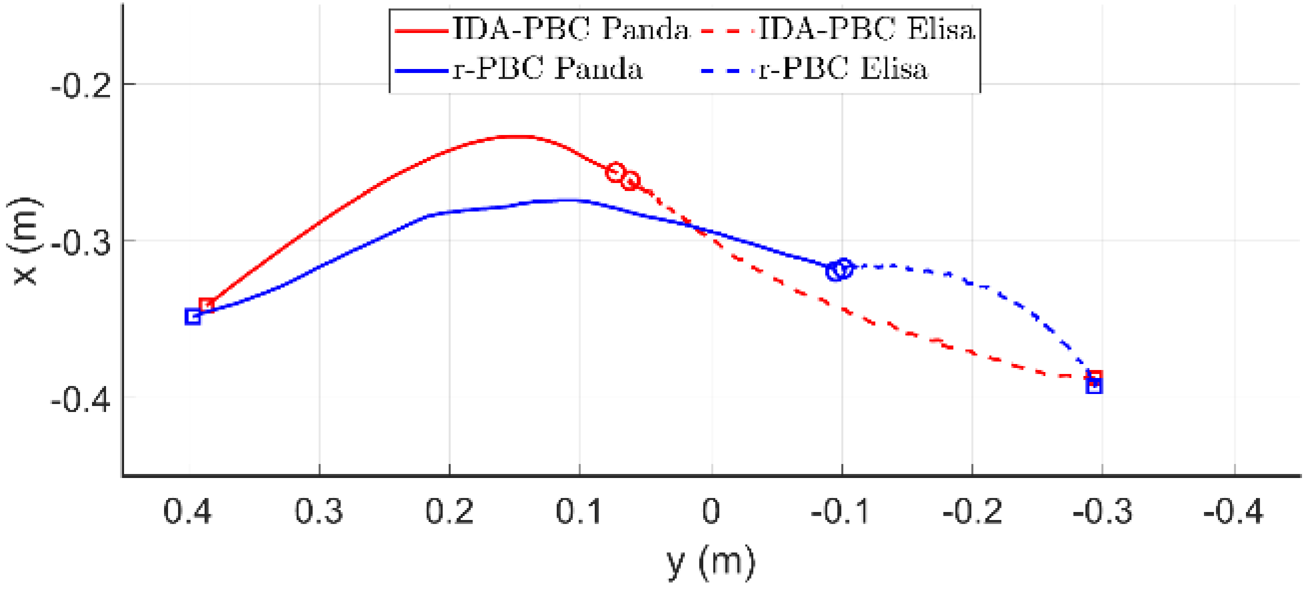
Comparison with State-of-the-Art (200-400 ms)



Comparison with State-of-the-Art (1000-1200 ms)