Multi-UAV Bilateral Shared Control and Decentralization

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MAX-PLANCK-GESELLSCHAFT

Human Perception, Cognition and Action
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Group picture

Human/Multiple-Mobile-Robot Interaction: Why?

A mutually-beneficial interaction

Human assistance still mandatory:

- in highly **complicated** environment (dynamic, unpredictable, cluttered)
- whenever **cognitive processes** are needed

Human

Robotic assistance needed to **extend** the human *perception* and *action* abilities

- higher **precision** and **rapidity**
- multi-scale **telepresence** (microscopic, macroscopic, planetary)

Multi-robot Mobile System

Multiple: more **effective** and **robust** than a single complex one

Mobile: more **flexible** and **pervasive** than fixed ones

*Large number of **applications***:

- coverage, exploration, mapping, surveillance, search and rescue, sensor networks, localization and tracking, mobile infrastructures, transportation,cooperative manipulation
- modular robotics
- nano-robot medical procedures

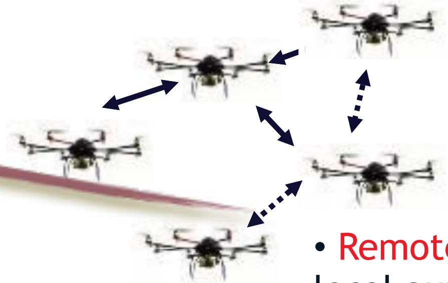
Bilateral Teleoperation of Multiple Aerial Robots

Human Operator

Haptic Interface

Communication Channel

Multi-UAV System



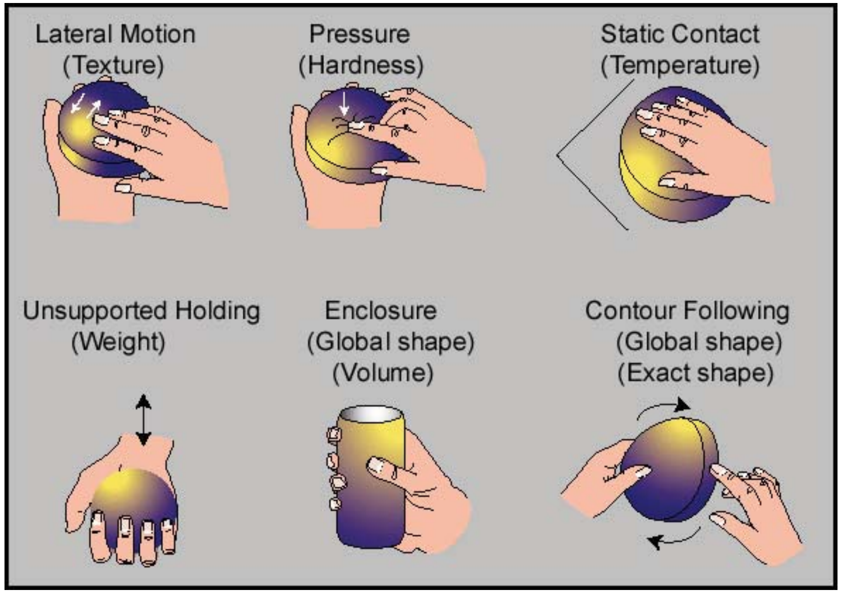
Remote Environment

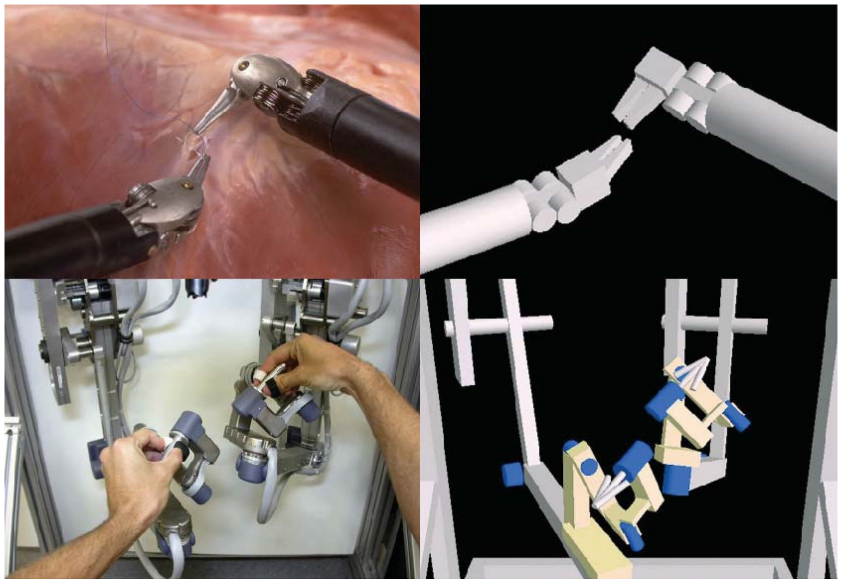
- Human operator gives **high-level motion commands** and receives a suitable **force feedback**

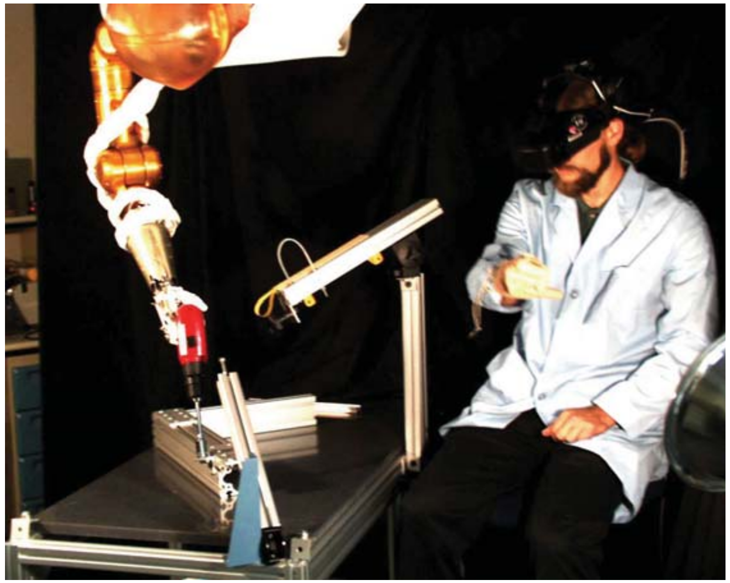
- Remote multi-UAVs possess local autonomy
    - Keep the formation
    - Avoid obstacles
    - Perform local tasks
    - Gather a map
    - Pick and place operations
    - Cooperative Grasping

Haptic feedback

- The sense of touch carries rich and "fast" information
- Widely exploited in teleoperation applications (e.g., telesurgery)

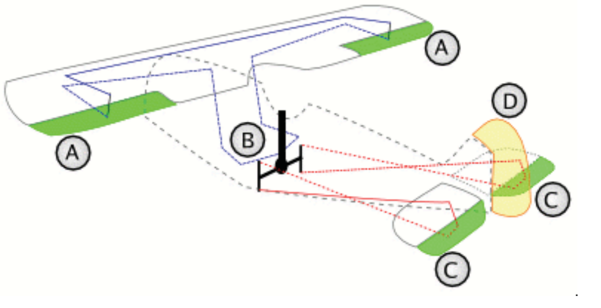




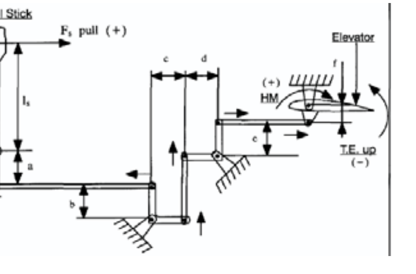


Haptic feedback


- Feeling force cues can be crucial for piloting a vehicle
- The force felt on the steering wheel informs car pilots on the amount of grip between tires and road

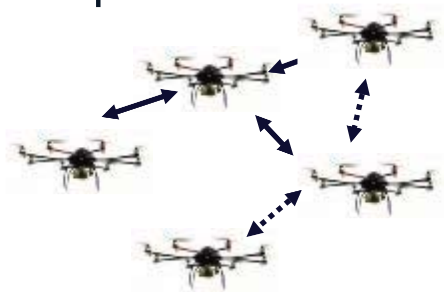


- An airplane pilot can judge the aerodynamic load or occurrence of wind gusts
  - He can "feel" the state of the aircraft
- Often fly-by-wire systems are complemented with artificial force feedack

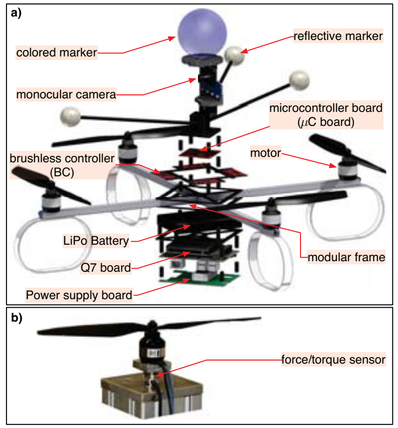



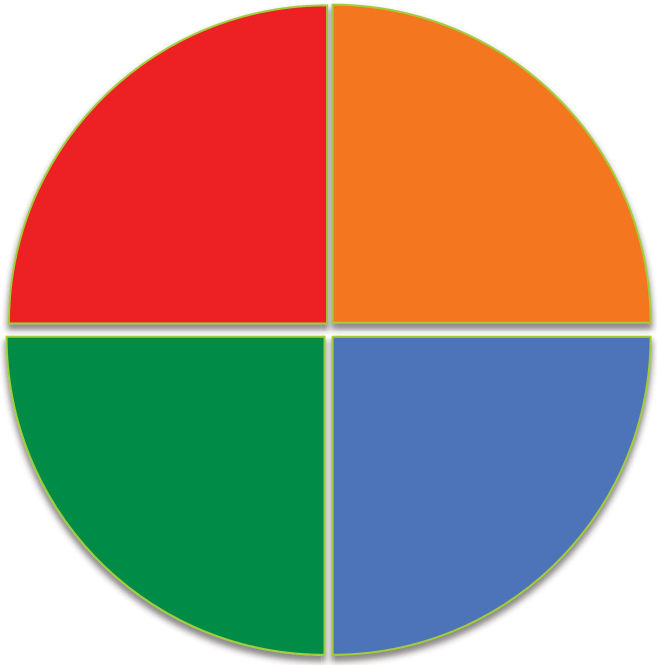
Ingredients

Collective behavior of multiple robots

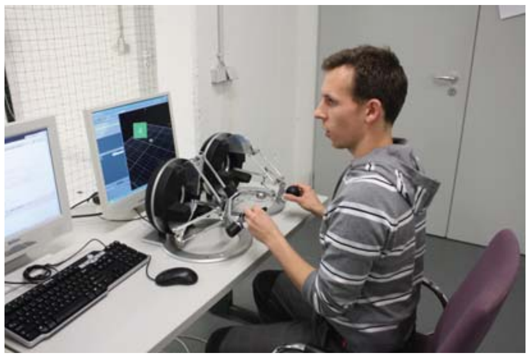


Robust flight control

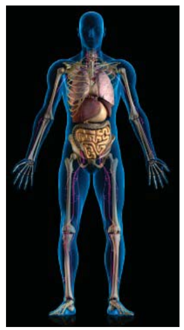




Bilateral Teleoperation and Telepresence

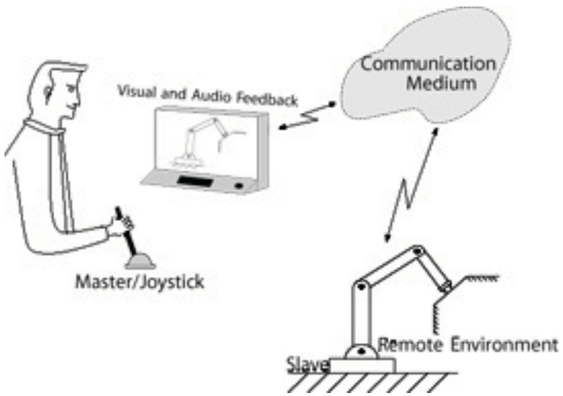


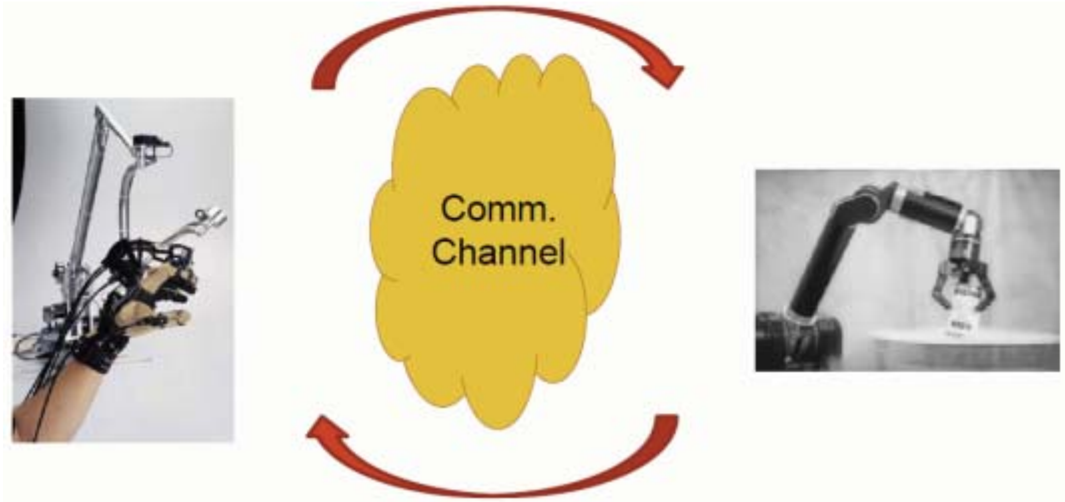
Human evaluation and user studies

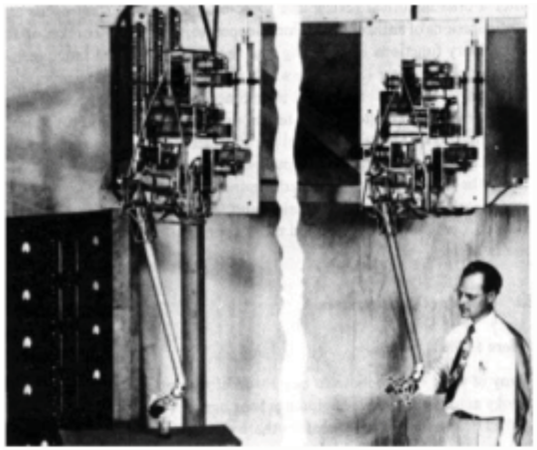


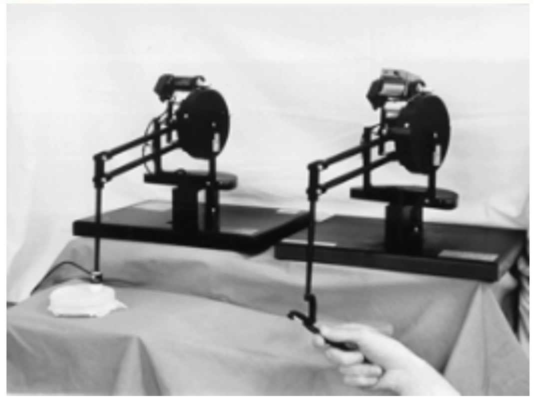
Bilateral Teleoperation

- "Remote" coupling between two (or more) mechanical systems (robots)
  - Master: local robot interacting with a human operator
  - Slave: remote robot(s) interacting with the environment

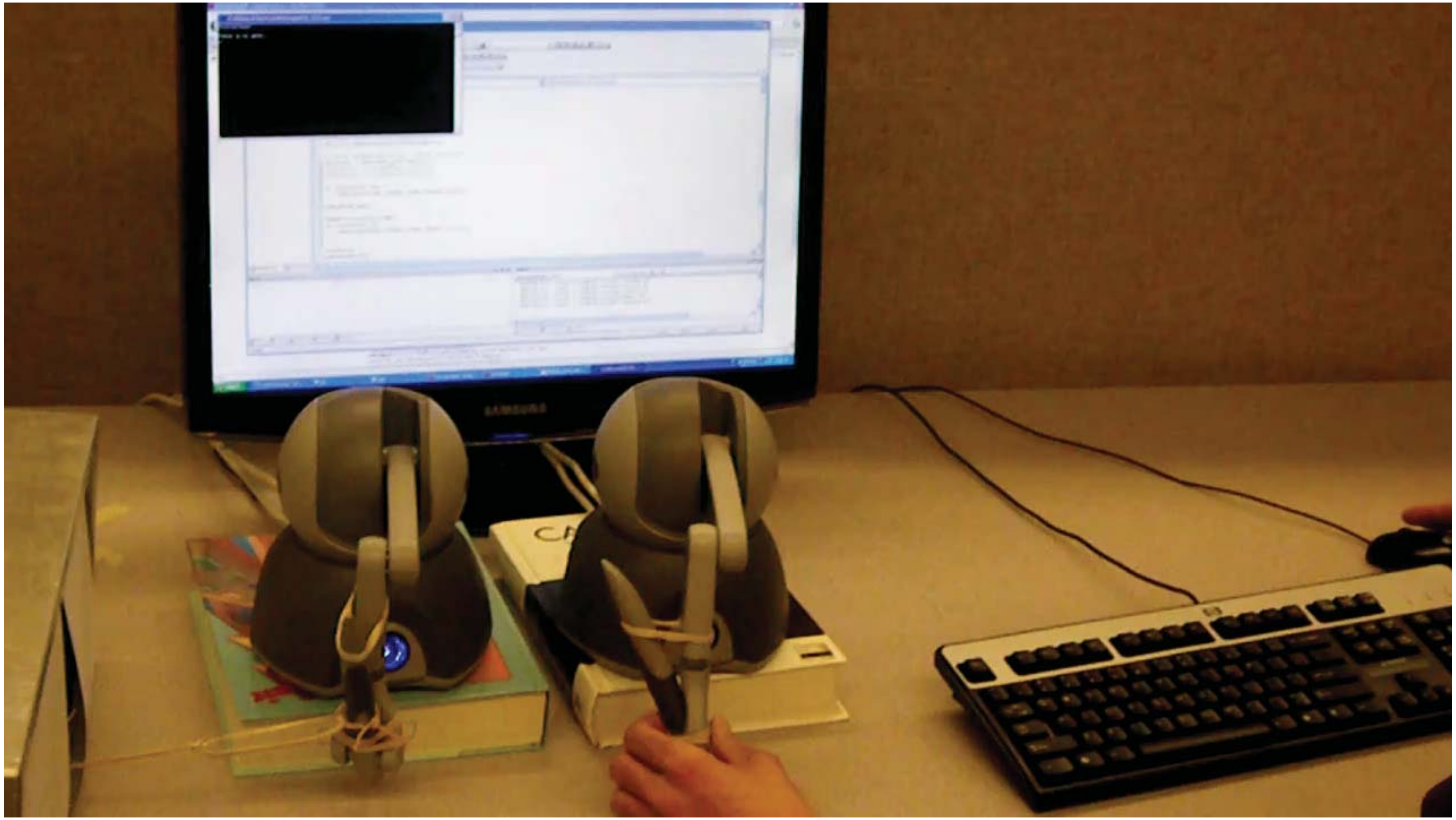








An Example of Bilateral Teleoperation



- Instabilities mainly due to communication delays and discretization

Differences w.r.t. Conventional Teleoperation

1. Kinematic dissimilarity

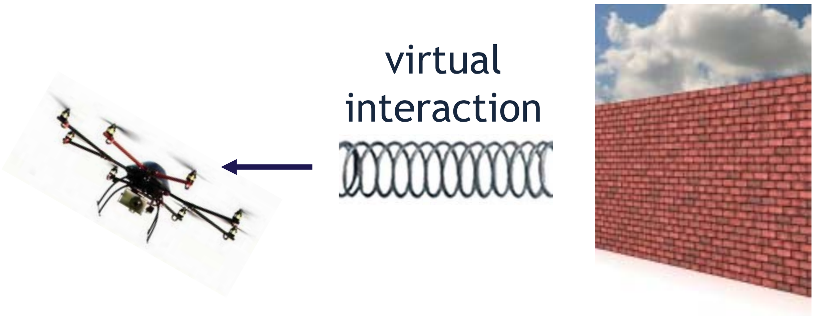
Master side:
limited workspace

Slave side (UAVs):
unlimited workspace

E.g., the **position** of the master controls the **velocity** of the slave

2. **No physical contact** between environment and slave side

- avoid contact to **prevent crash**
- interaction **forces** must/can be **designed** (e.g., repulsive/attractive)



3. High motion **redundancy** of the slave

- large gap in the number of DOFs (master vs slave):

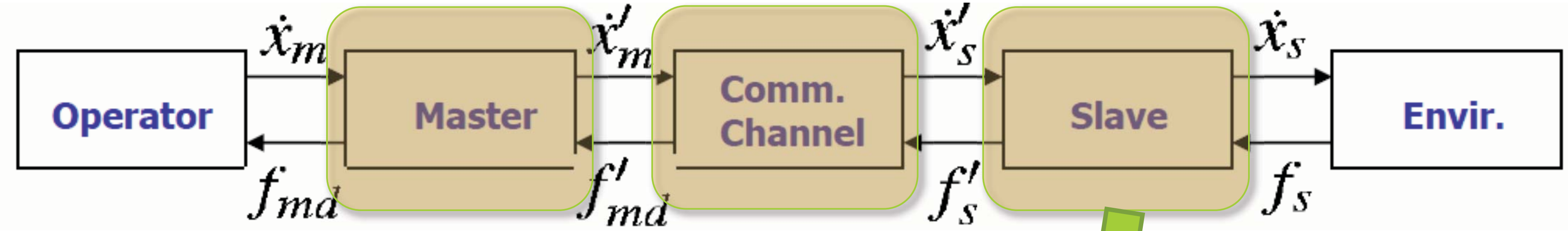
master: usually
3 trans. + 3 rot. DOFs

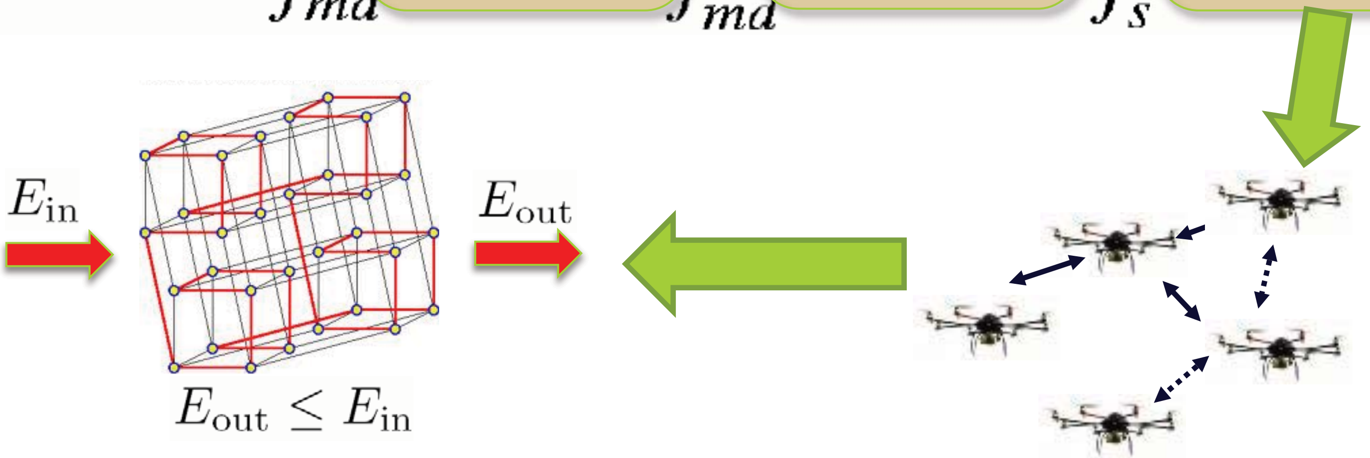
slave: made of
several Robots

Stability in Bilateral Teleoperation

- Control Goals of a Bilateral Teleoperation System
  - Ensure a stable Teleoperation behavior (stable reactions to Operator and Environment actions)
  - Ensure "transparency" (~ interaction slave/env = interaction master/human)

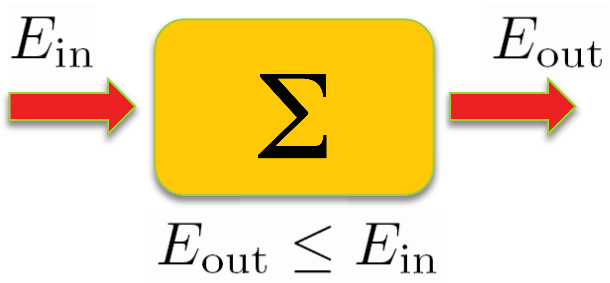
- How to do it? **A possibility**: make sure the **Master/Comm. Channel/Slave** system is (altogether) a passive system





Passivity

- **Passivity**: intuitively, something that does not produce internal energy



- A generic nonlinear system $\begin{cases} \dot{x} &= f(x) + g(x)u \\ y &= h(x) \end{cases}$

  is said to be passive if there exists a storage function

  $$V(x) \in \mathcal{C}^1 : \mathbb{R}^n \rightarrow \mathbb{R}^+$$

  such that $\dot{V} \leq y^T u$ or equivalently

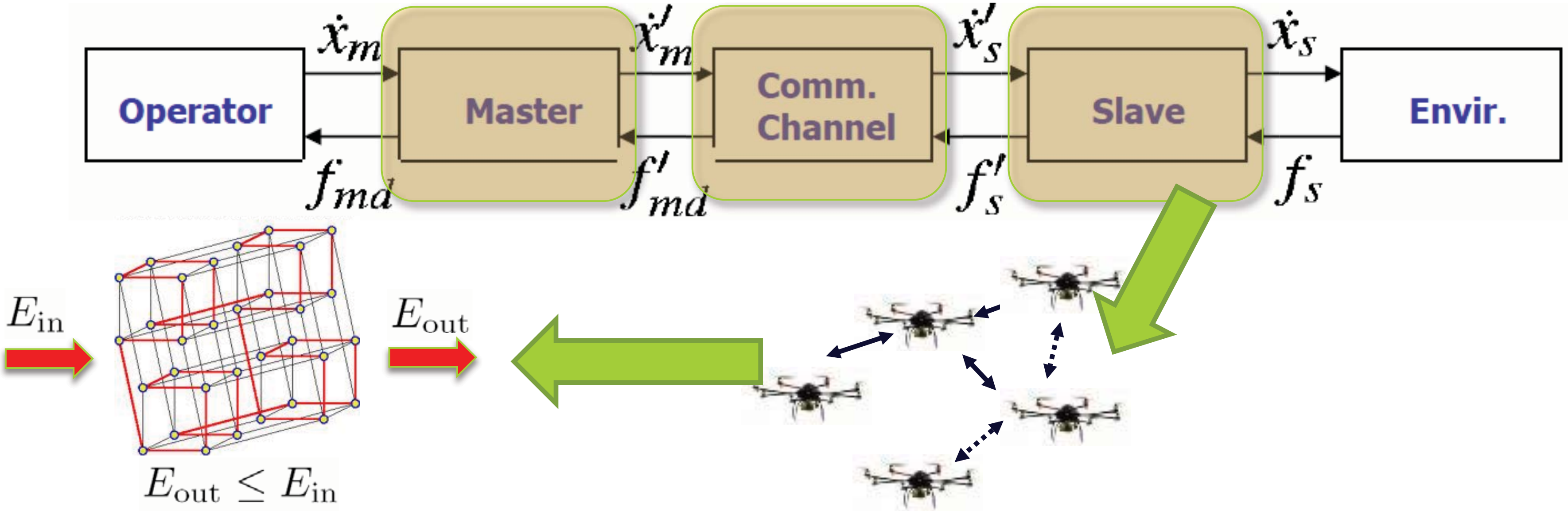
  $$\boxed{V(x(t))} \leq \boxed{V(x(t_0))} + \boxed{\int_{t_0}^{t} y^T(s)u(s)\mathrm{d}s}$$

  Current energy is at most equal to the initial energy + supplied energy from outside

- This condition can be interpreted as "no internal generation of energy"

Networked Dynamical System

- A very convenient possibility: model the slave as the (passive) interconnection of multiple agents



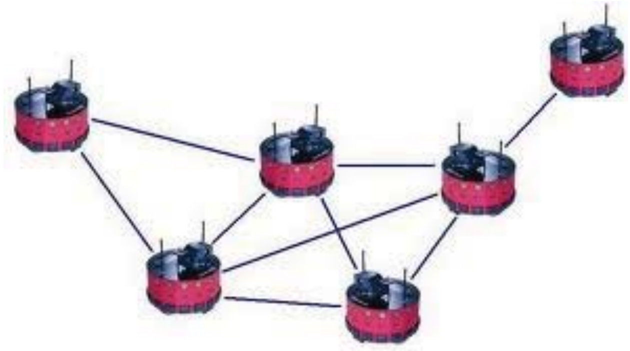
- Exploiting the port-Hamiltonian Modeling formalism

$$\begin{cases} \dot{x} = [J(x) - R(x)]\dfrac{\partial H}{\partial x} + g(x)u, \quad J(x) = -J^T(x),\ R(x) \geq 0 \\ y = g^T(x)\dfrac{\partial H}{\partial x} \end{cases}$$

$$H(x) \geq 0$$

$$\dot{H} = -\frac{\partial^T H}{\partial x} R(x) \frac{\partial H}{\partial x} + \frac{\partial^T H}{\partial x} g(x) u \leq y^T u$$

Multi-Agents



Multi-Agents

Formation Control

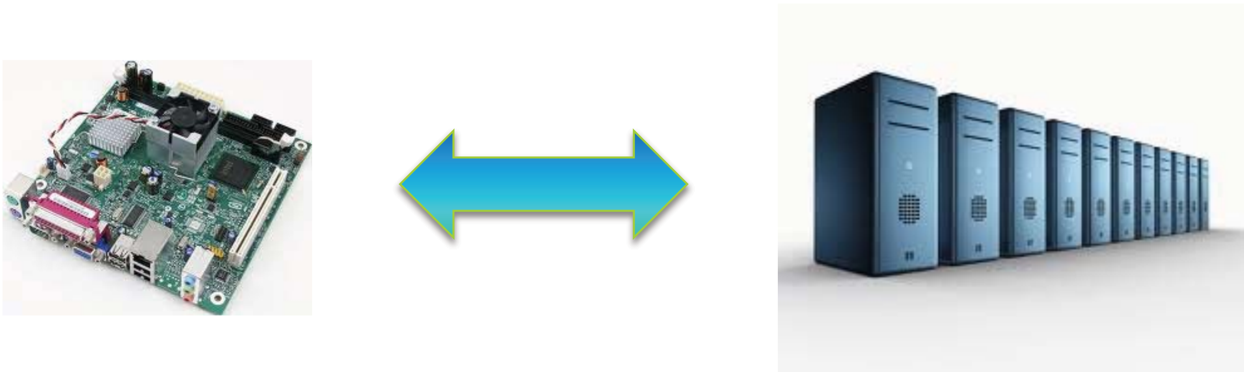
Keep a desired spatial configuration despite the large number of agents

State Synchronization

An agreement by multiple systems on a common state

Decentralization

- Decentralized: limited sensing/communication and/or computing power
- Every agent must elaborate the gathered information to run its local controller
- The controller complexity is related to the amount of needed information
- If the whole state is needed, the complexity (~ computing power) increases with the number of agents
  - May easily become infeasible
  - And would need to know the whole state...

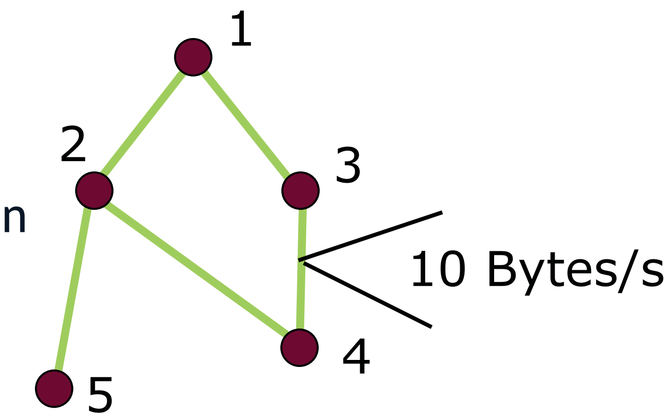


Decentralization

- Decentralization: the limited sensing/communication/computing power induce an "information/interaction graph" among the agents

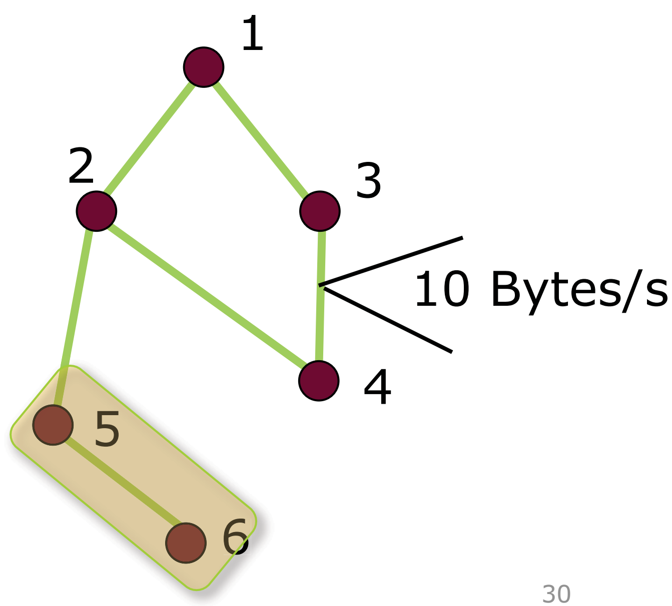
- The nodes represent the agents

- The edges represent an interaction or information flow
  - Sensed
  - Communicated
  - Elaborated



- **Decentralization:** on each edge, size of information flow is constant ($O(1)$ per neighbor)

- example: adding node 6 does not increase the information needed by nodes 1,2,3,4



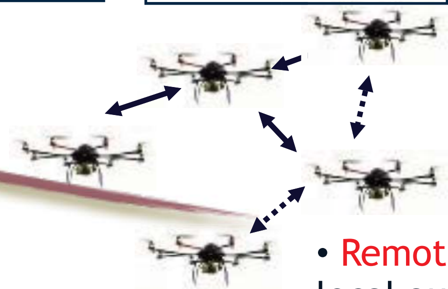
Bilateral Teleoperation of Multiple Aerial Robots

Human Operator

Haptic Interface

Communication Channel

Multi-UAV System



Remote Environment

- Human operator gives **high-level motion commands** and receives a suitable **force feedback**

- Remote multi-UAVs possess local autonomy
    - Keep the formation
    - Avoid obstacles
    - Perform local tasks
    - Gather a map
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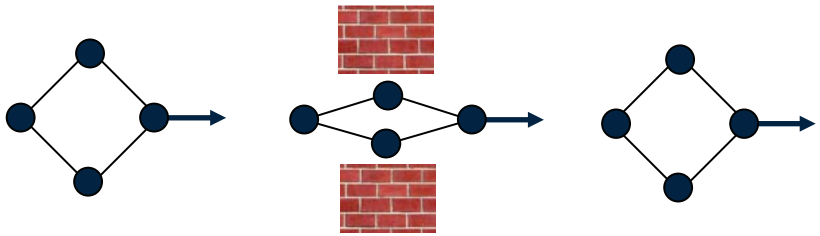
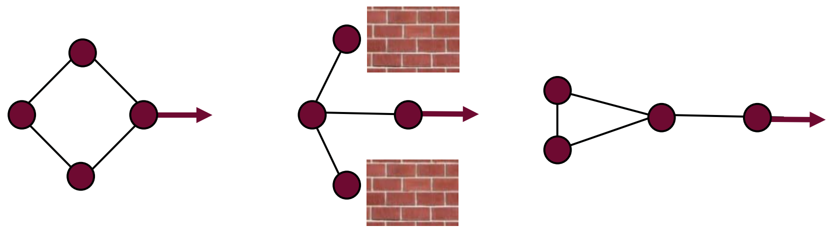
    - Cooperative Grasping

Two Group Teleoperation Approaches

Constant Topology



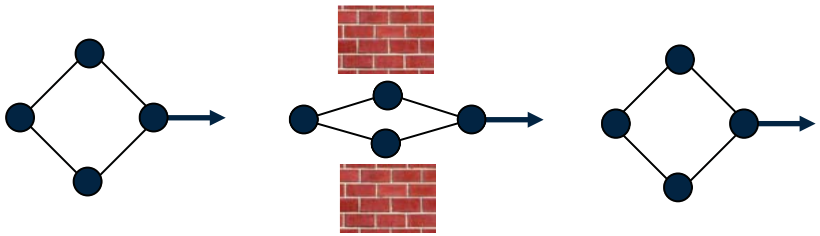
Unconstrained Topology



- General **"tele-navigation"** framework
- Basis for building any **higher-level exploration** or **generic cooperative task**

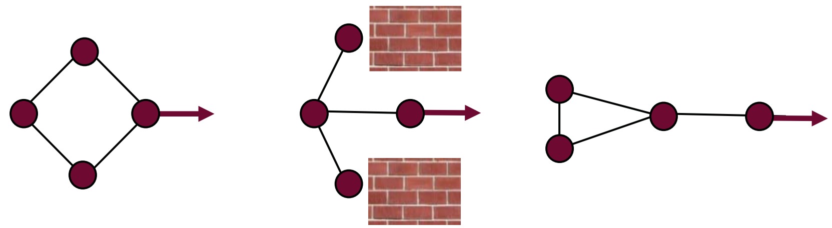
Differences

Constant Topology



- Fixed graph topology
- Robots are constrained to keep a desired formation (with possible deformations)
- The human operator can control the remaining degrees of freedom
- Usually, good for precise measurements (data fusion)

Unconstrained Topology



- Time-varying graph topology
- Robots are loosely coupled together (can gain/lose neighbors)
- Robots can decide to split or to join depending on constraints or tasks
- The human operator controls the motion of a subset (e.g., one leader)
- Appropriate for "loose" tasks, e.g., coverage, persistent patrolling

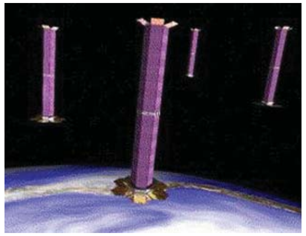
- In general, **force feedback** = mismatch between **commanded "motion task"** and **its actual realization**

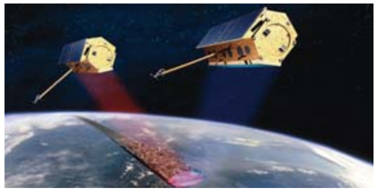
Constant Topology: Objectives and Measures

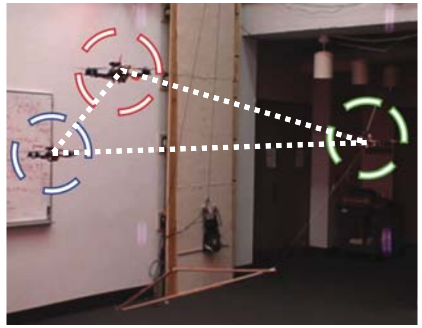
In the semi-rigid formation case a **desired shape** is given and must be **maintained**

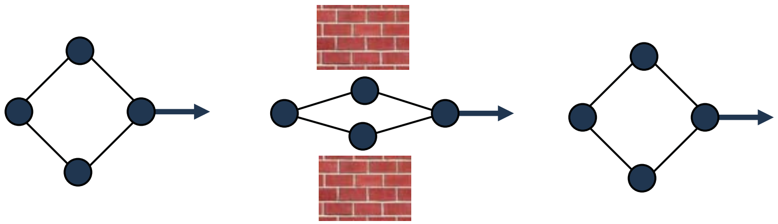
Possible uses:

- taking precise **measurements**
- achieving **optimal communication**
- transportation









A shape is typically **placement-invariant** and is defined by **constraints**

Inter-distances

- *rotational invariant*
- time-of-flight sensors, stereo cameras, structured light

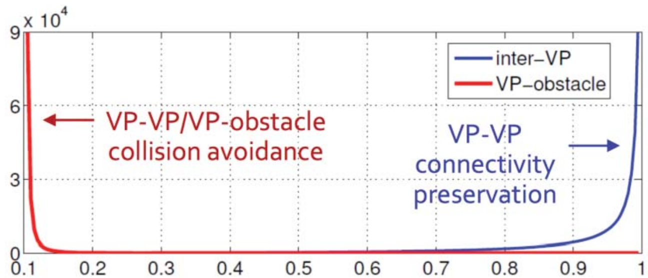
Relative-bearings

- *rotational and **scale** invariant*
- monocular camera

Constant Topology

- Shape defined through desired inter-distances $\|p_i - p_j\| \quad \forall i,j$
- Reference trajectory generation: $\dot{p}_i(t) := u_i^t + u_i^c + u_i^o$
- **Inter-distance** preservation term $u_i^c := -\sum_{j\in\mathcal{N}_i} \frac{\partial \varphi_{ij}^c(||p_i - p_j||^2)^T}{\partial p_i}$
- **Obstacle** avoidance term $u_i^o := -\sum_{r\in\mathcal{O}_i} \frac{\partial \varphi_{ir}^o(||p_i - p_r^o||)^T}{\partial p_i}$
- Velocity **command** from the user $u_i^t := \lambda q(k)$
- 3-DOF haptic device $M(q)\ddot{q} + C(q,\dot{q})\dot{q} = \tau + f$

- overall shape autonomously deforms reacting to obstacles
- **reversible** deformations are allowed



Semi-rigid Formation using Distances

- Teleoperation force feedback:
- **force feedback** term $\tau(t) := -B\dot{q} - K(q - \bar{y}(k))$
- $\bar{y}(k)$ passive set modulation of $y(k) := \frac{1}{\lambda N} \sum_{i=1}^{N} (\dot{x}_i + u_i^o)$
  - guarantees passivity in presence of delay and discretization
  - can be any signal (our case: velocity)

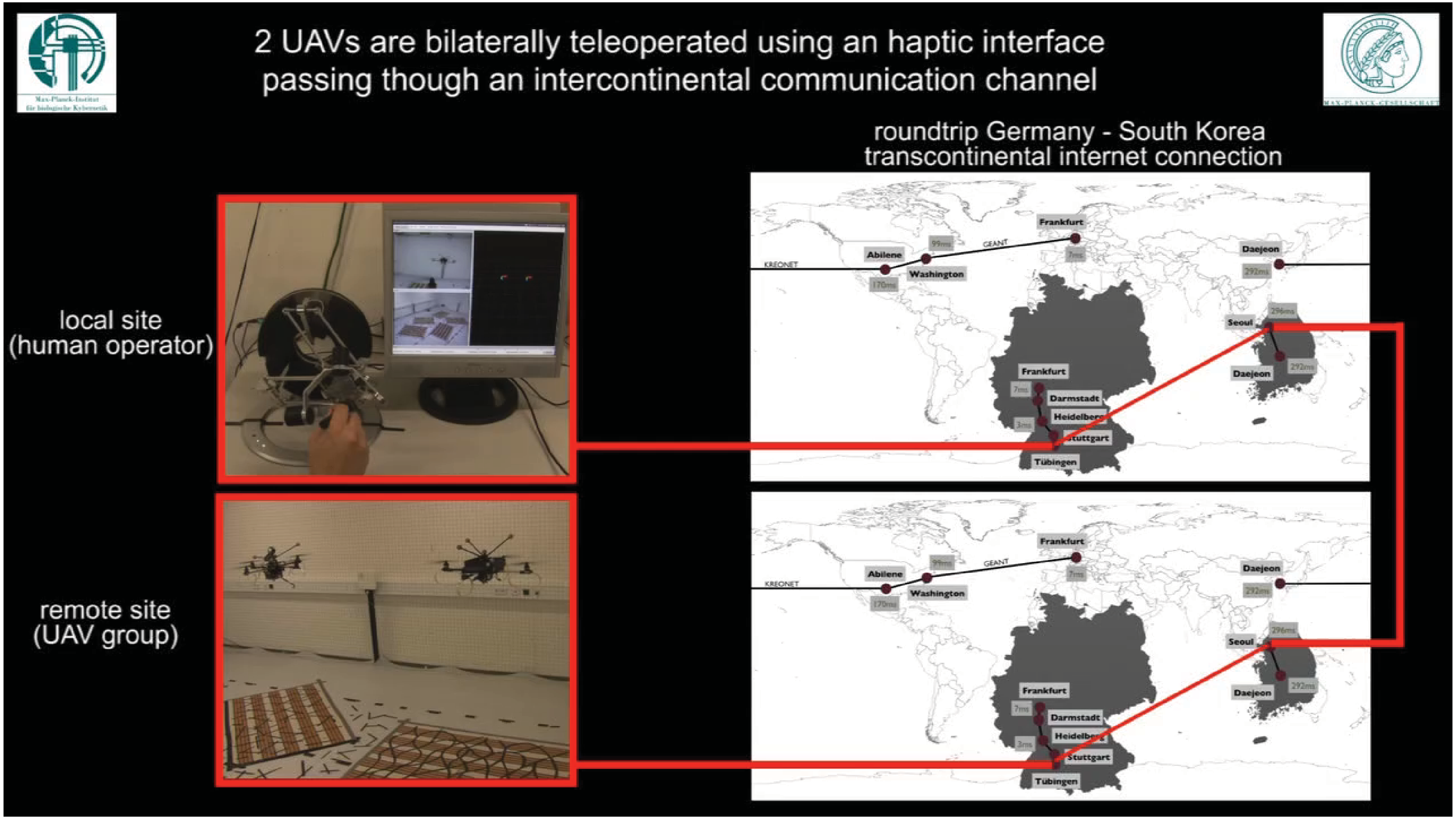
- **Mismatch** between commanded and actual motion
- **Obstacle repulsion**

- Main results
- The **overall teleoperation system is passive (stable when interacting with human/ environment**)
- At steady state $(\ddot{q}, \dot{q} \to 0,\ E(k) > 0\ \forall k \geq 0, \text{ and } (x_i, \dot{x}_i) = (p_i, \dot{p}_i))$
  - $q(t) \to \frac{1}{\lambda N_t} \sum_{i=1}^{N} \dot{x}_i, \quad f(t) \to \frac{K}{\lambda} \frac{N - N_t}{N N_t} \sum_{i=1}^{N} \dot{x}_i$ if $\sum_{i=1}^{N} u_i^o = 0$ (e.g. no obstacles)
  - $f(t) \to -\frac{K}{\lambda} \frac{N + N_t}{N N_t} \sum_{i=1}^{N} u_i^o, \quad q(t) \to -\frac{1}{\lambda N_t} \sum_{i=1}^{N} u_i^o$ if $\sum_{i=1}^{N} \dot{x}_i = 0$ (e.g. stopped by obstacles)

Semi-rigid Formation using Distances

ICRA 2011

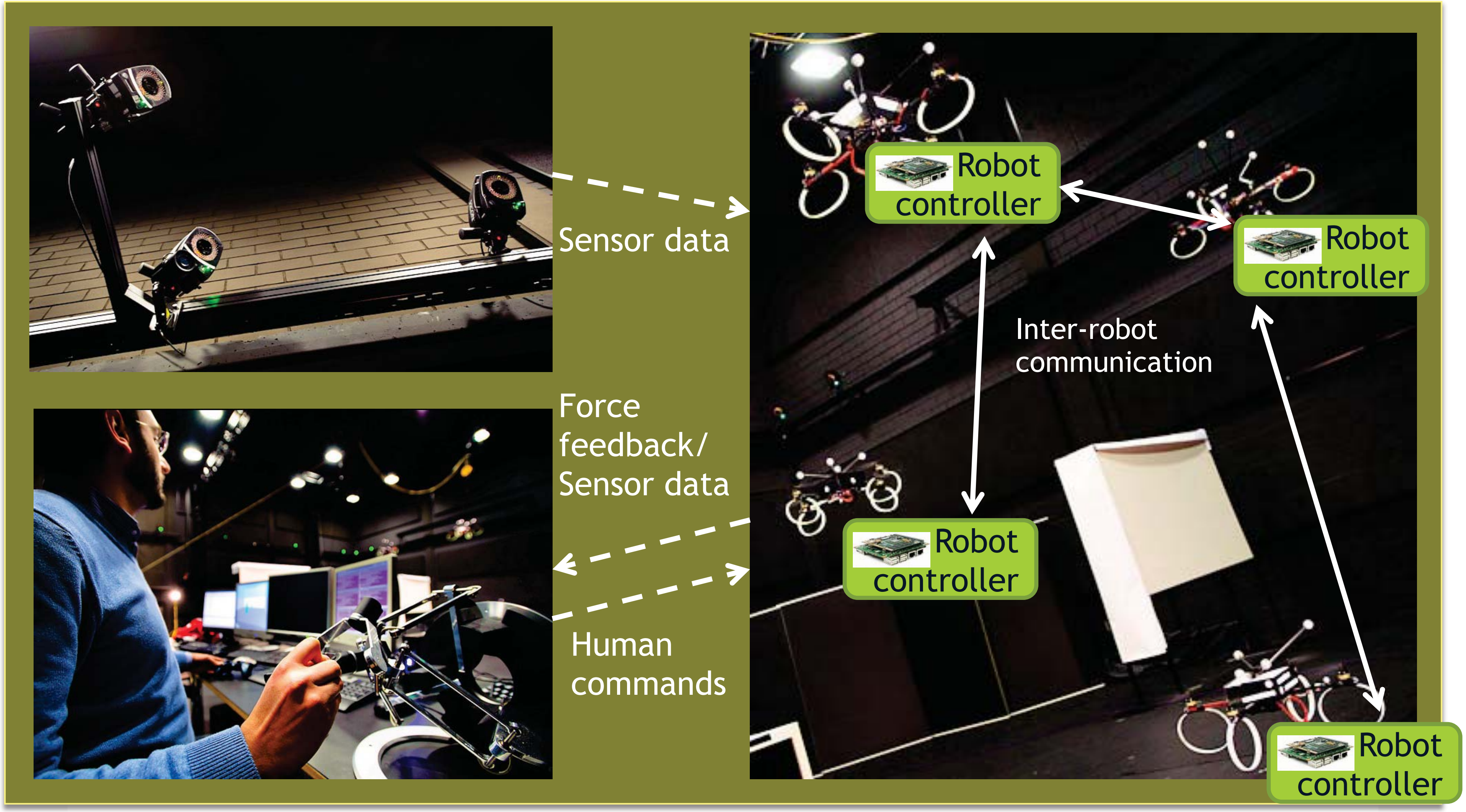
Semi-rigid Formation using Distances



Experiments on Intercontinental Haptic Control of Multiple UAVs, IAS 2012
Bilateral teleoperation experiment from **Korea** (Korea University) to **Germany** (MPI Biol. Cyb.)

Experimental Testbed

- Experimental environment



Hardware for Quadcotper UAV

Mikrokopter quadrocopter

- Customizable modular kit
- Atmel ATMEGA644 @ 20MHz
- Accelerometers + Gyros + Pressure sensor
- PWM motors
- Additional Payload: 0.7 kg ca.
- Battery Autonomy 15 min. ca
- Serial connections:
- wired with Seco Qseven
- wireless (Xbee) with any PC

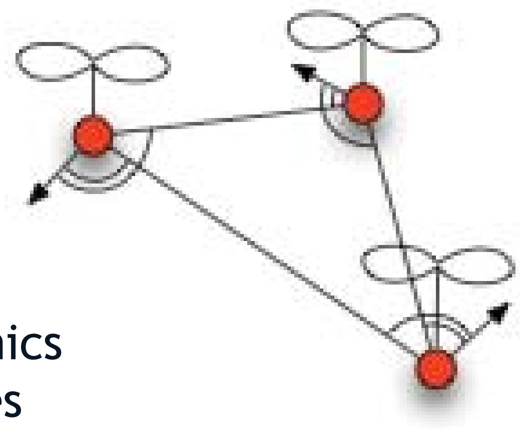
Seco **Qseven** Quadmo747

- Intel Atom Z500 1,6 GHz
- 1 GB ram
- Intel graphic card
- Usb, ethernet, sata,…

Semi-rigid Formation using Bearings

Shape defined through desired relative-bearings

$$^{i}\boldsymbol{\beta}_{ij} = {}^{i}R\,\boldsymbol{p}_{ij}/\delta_{ij}$$



- **reversible** deformations are allowed
- Each robot tracks a trajectory with first-order dynamics representative of the quadrotor actuation capabilities

$$\begin{pmatrix} \dot{\boldsymbol{p}}_i \\ \dot{\psi}_i \end{pmatrix} = \begin{pmatrix} R_i & \mathbf{0}_3 \\ \mathbf{0}_3^T & 1 \end{pmatrix} \begin{pmatrix} \boldsymbol{u}_i \\ w_i \end{pmatrix} \qquad (\boldsymbol{u}_i, w_i) = (\boldsymbol{u}_i^f, w_i^f) + (\boldsymbol{u}_i^h, w_i^h)$$

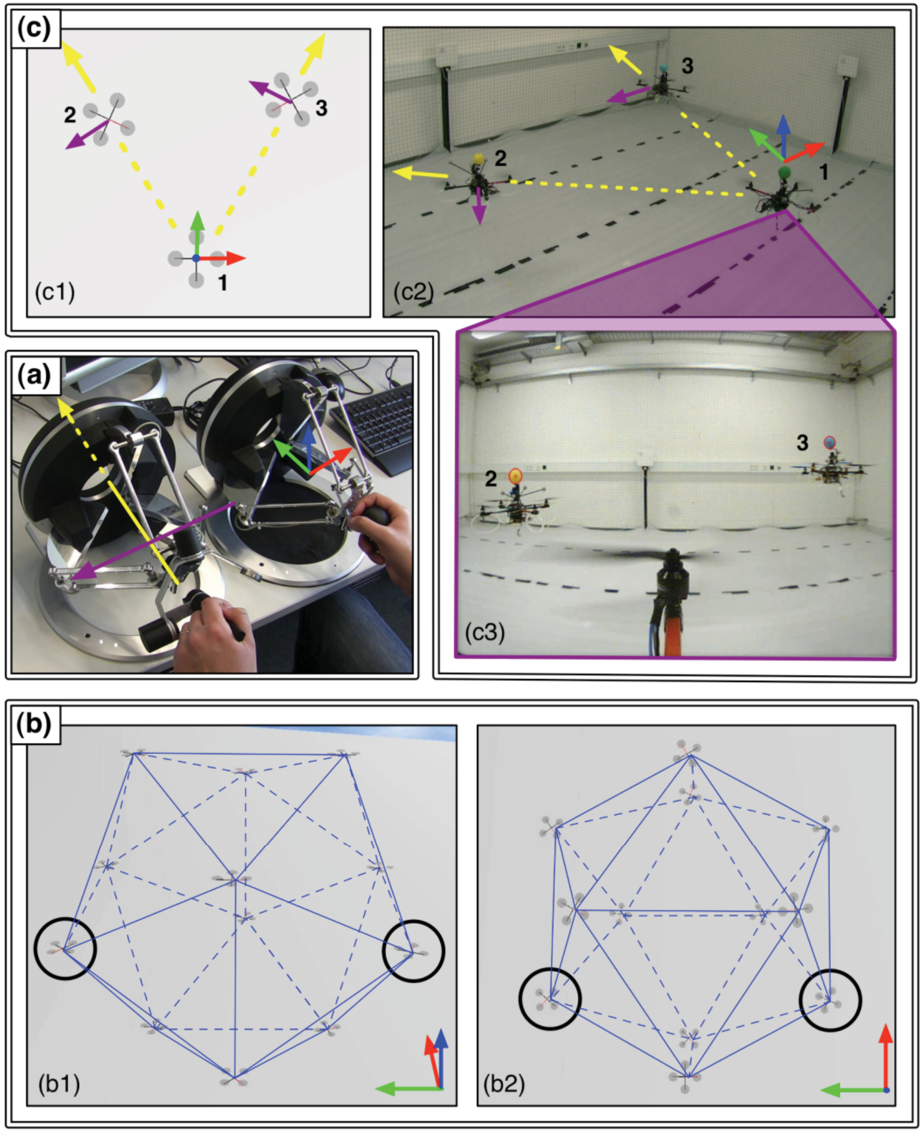
- The team maintains the **desired shape**
  - only measuring relative angles
  - without collapsing/expanding
- Human controls the **collective motion** in the "null-space" of the formation control action
  - translation velocity
  - expansion rate
  - rotational rate

Semi-rigid Formation using Bearings

- Use relative bearings (angles) for formation control
- Relative bearings can be directly retrieved from onboard cameras
- Lack of metric (distance) measurements

- The spatial formation is defined up to **5 dofs**:
  - Collective translation vel. $\boldsymbol{\nu} \in \mathbb{R}^3$
  - Synchronized expansion rate $s \in \mathbb{R}$
  - Synchronized rotation rate $w \in \mathbb{R}$

- The human operator controls these **5 dofs** with **2 haptic devices**
  - Force feedback: mismatch between the desired and actual commands



IROS 2011, IJRR (under review)

Force Feedback

Dynamics of the two masters (3DOF + 2DOF)

$$M_t(\boldsymbol{x}_t)\ddot{\boldsymbol{x}}_t + C_t(\boldsymbol{x}_t, \dot{\boldsymbol{x}}_t)\dot{\boldsymbol{x}}_t = \boldsymbol{\tau}_t + \boldsymbol{f}_t$$
$$M_r(\boldsymbol{x}_r)\ddot{\boldsymbol{x}}_r + C_r(\boldsymbol{x}_r, \dot{\boldsymbol{x}}_r)\dot{\boldsymbol{x}}_r = \boldsymbol{\tau}_r + \boldsymbol{f}_r$$

Overall-motion Commands

$$\boldsymbol{\nu} = \lambda_t \boldsymbol{x}_t, \quad \begin{pmatrix} s \\ w \end{pmatrix} = \begin{pmatrix} \lambda_s & 0 \\ 0 & \lambda_w \end{pmatrix} \boldsymbol{x}_r$$

Force Feedback: **mismatch** between desired and actual

- translational velocity $\boxed{\boldsymbol{\tau}_t = -B_t\dot{\boldsymbol{x}}_t - K_t\boldsymbol{x}_t - K_t^e(\boldsymbol{x}_t - \boldsymbol{z}_t)}$

where $$\boldsymbol{e}_t = \boldsymbol{x}_t - \frac{1}{N}\sum_{i=1}^{N} \boldsymbol{z}_{ti} = \boldsymbol{x}_t - \boldsymbol{z}_t \qquad \boxed{\frac{1}{\lambda_t}{}^1R_i\left(\dot{\boldsymbol{p}}_{\mathcal{B}_i} + \gamma_{12i}(\lambda_s x_s \boldsymbol{\beta}_{i1} - \lambda_w x_w \delta_{12} S \boldsymbol{\beta}_{i1})\right) =: \boldsymbol{z}_{ti}}$$

- expansion/rotation rate $\boxed{\boldsymbol{\tau}_r = -B_r\dot{\boldsymbol{x}}_r - K_r\boldsymbol{x}_r - K_r^e(\boldsymbol{x}_r - \boldsymbol{z}_r)}$

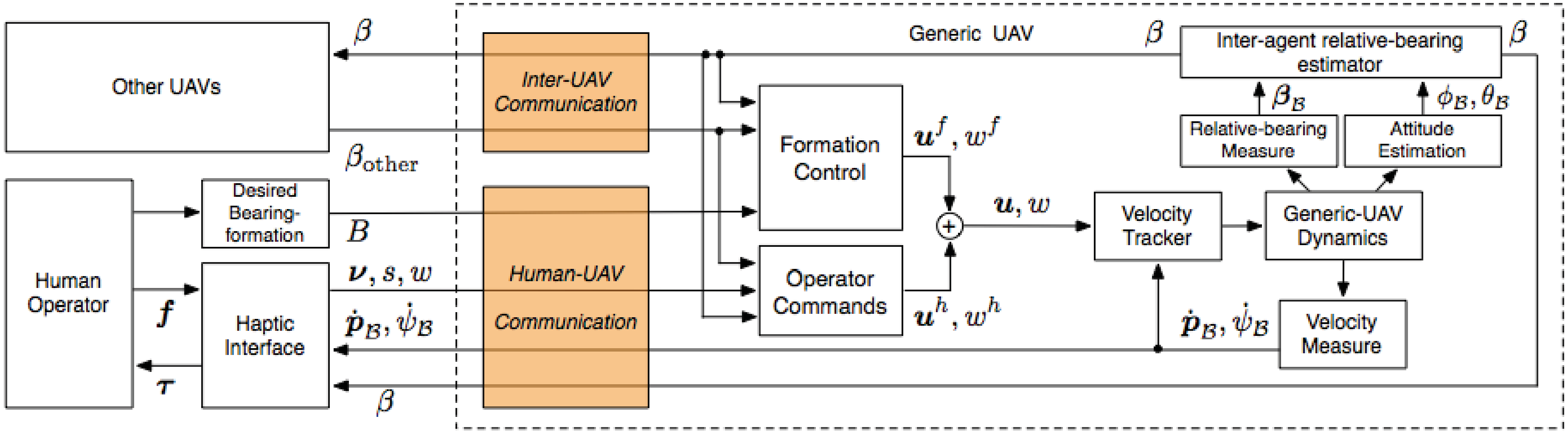
where $$e_s = x_s - \frac{1}{N}\sum_{i=1}^{N} z_{si} = x_s - z_s \qquad \boxed{\frac{1}{\lambda_s\gamma_{12i}}({}^iR_1\boldsymbol{\nu} - \dot{\boldsymbol{p}}_{\mathcal{B}_i}) \cdot \boldsymbol{\beta}_{i1} =: z_{si}}$$

$$e_w = x_w - \frac{1}{N}\sum_{i=1}^{N} z_{wi} = x_w - z_w \qquad \boxed{\frac{\dot{\psi}_{\mathcal{B}_i}}{\lambda_w} = z_{wi}}$$

Semi-rigid Formation using Bearings

Simulations with 12 quadrotor UAVs **IROS 2011, IJRR (under review)**

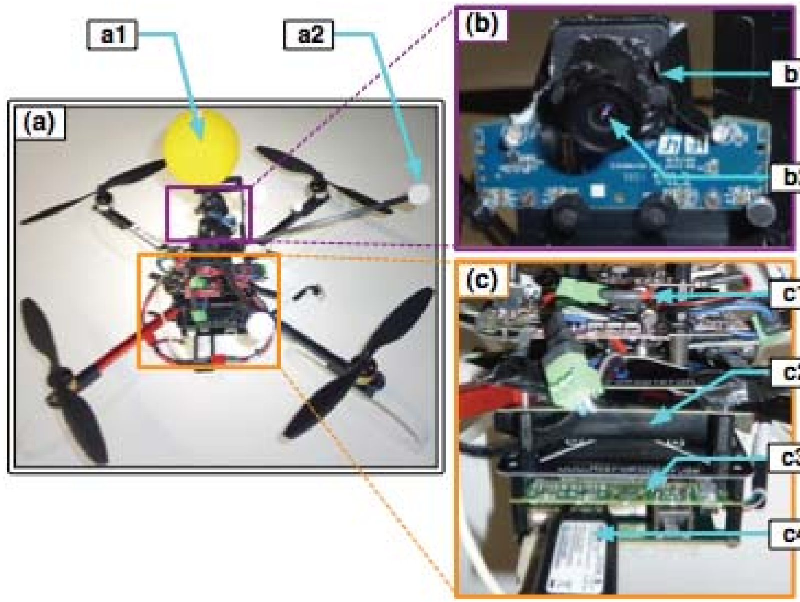
System Architecture and Implementation



3 Quadrotors +

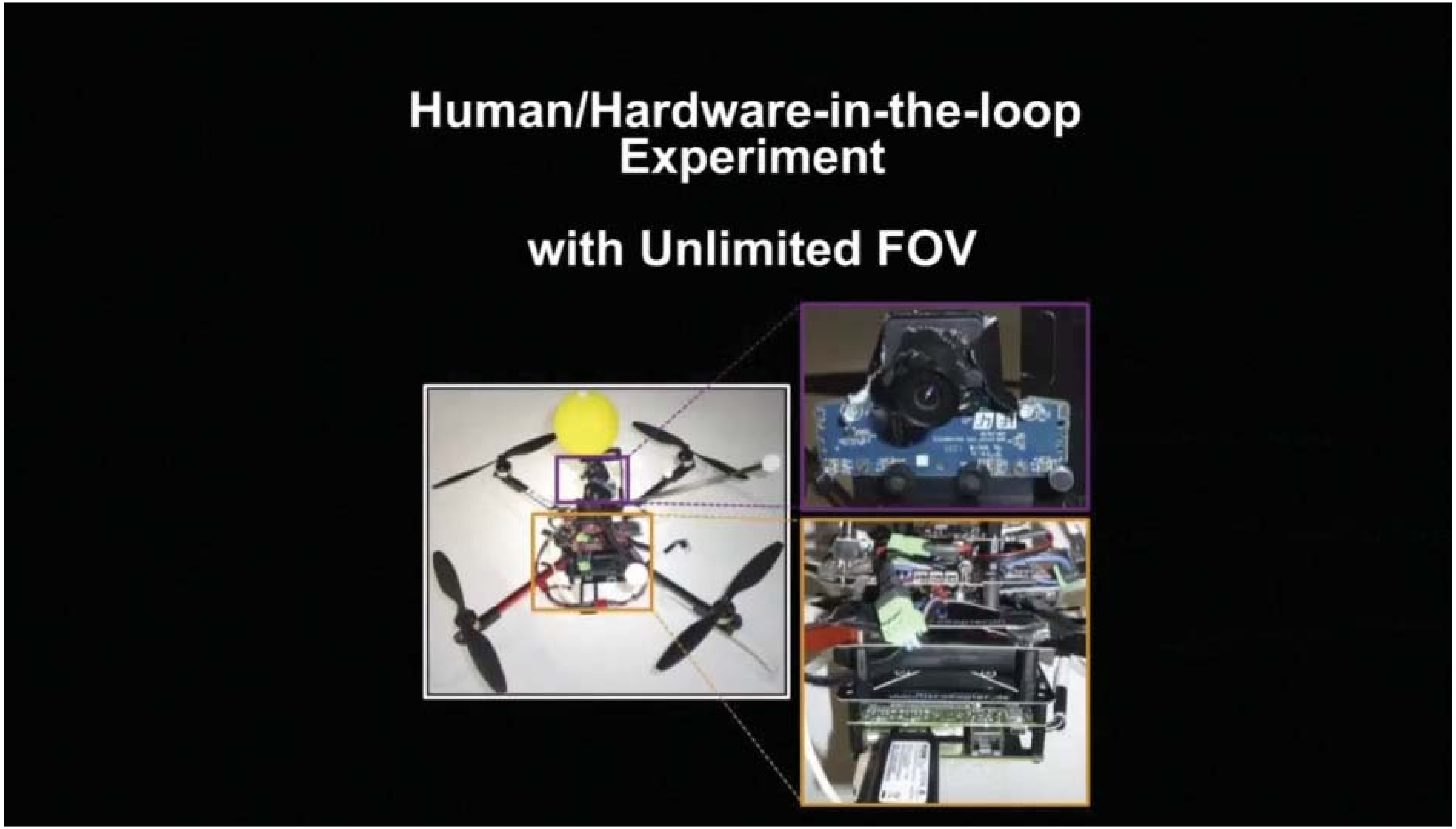
3 Onboard Cameras +

3 Onboard PCs



Semi-rigid Formation using Bearings

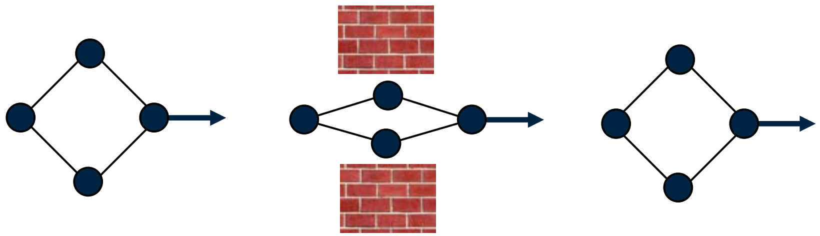
Experiments with 3 quadrotor UAVs



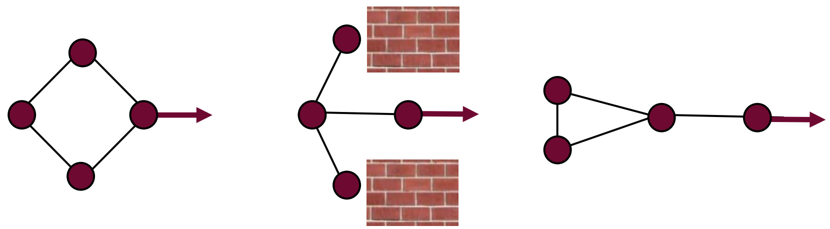
IROS 2011, IJRR (under review)

Two Group Teleoperation Approaches

Constant Topology



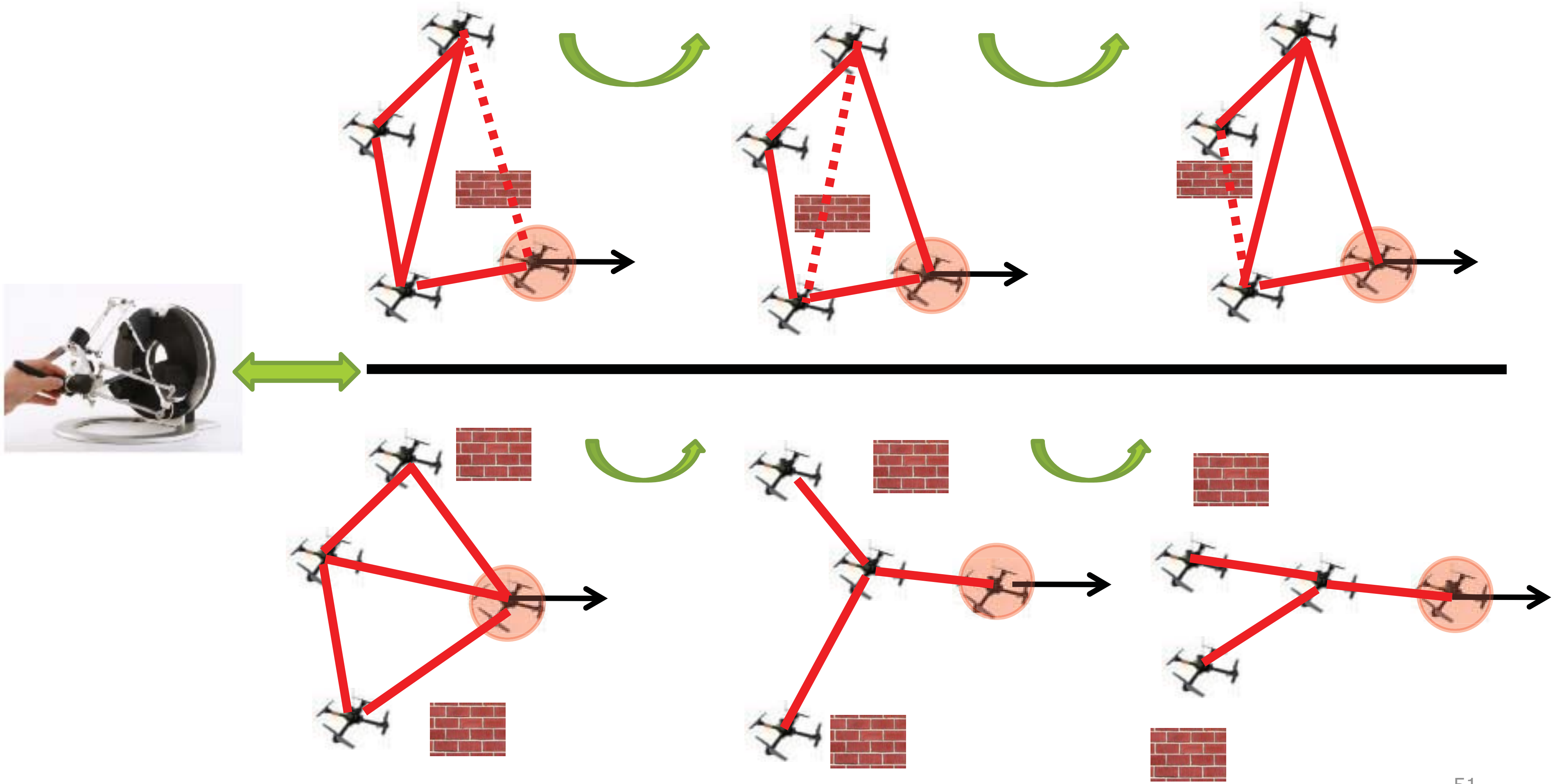
Unconstrained Topology



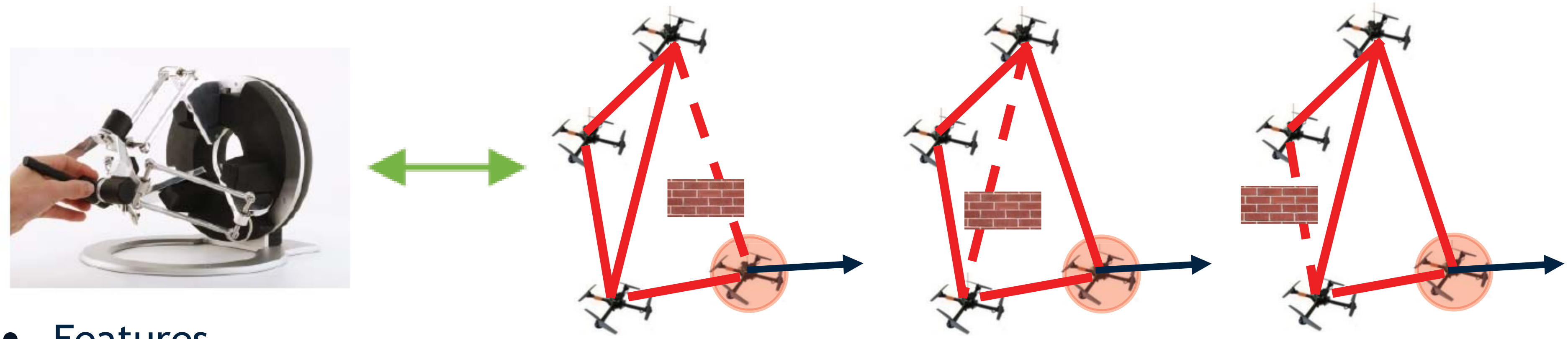
- General **"tele-navigation"** framework
- Basis for building any **higher-level exploration** or **generic cooperative task**

Unconstrained Topology

- Time-varying graph topology because of sensing/task constraints
  - Sensing model (e.g., maximum range, loss of visibility)
  - Execution of extra tasks in parallel



Unconstrained Topology



- Features
  - decentralized design (1-hop communication/sensing)
  - single communication channel among the leader and the human operator (master-side)
  - flexible formation: split/join due to
    - **sensing/communication constraints**
    - execution of **extra tasks** in parallel
  - Autonomy in avoiding obstacles and inter-agent collisions

- Challenges
  - Time-varying topology: ensure stability despite a switching dynamics
  - Guarantee an overall stable teleoperation system (~ passivity) also in presence of delays
  - Maintain group connectivity

Agent Model

- Every agent is modeled as a free-floating mass in $\mathbb{R}^3$ with Energy $\mathcal{K}_i = \frac{1}{2}p_i^T M_i^{-1} p_i$

$$\boxed{\begin{cases} \dot{p}_i = F_i^a + F_i^e - B_i M_i^{-1} p_i \\ v_i = \frac{\partial \mathcal{K}_i}{\partial p_i} = M_i^{-1} p_i \end{cases}} \qquad i = 1, \ldots, N$$

- $p_i \in \mathbb{R}^3$ is the agent momentum and $v_i \in \mathbb{R}^3$ the agent velocity. Let also $x_i \in \mathbb{R}^3$, with $\dot{x}_i = v_i$, be the agent position

- $M_i \in \mathbb{R}^{3\times 3}$ is the agent Inertia matrix

- $B_i \geq 0 \in \mathbb{R}^{3\times 3}$ is a velocity damping term (either naturally present or artificially added)

- Force (input) $F_i^a \in \mathbb{R}^3$ represents the interaction (coupling) with the other agents

- Force (input) $F_i^e \in \mathbb{R}^3$ represents the interaction with the "external world" (e.g., obstacles or master side)

Agent Model

- **Remarks:**

- In PHS terms, an agent represents an atomic element storing kinetic energy

$$\mathcal{K}_i = \frac{1}{2} p_i^T M_i^{-1} p_i$$

and endowed with two power ports (F_i^a, v_i) and (F_i^e, v_i)

- We consider a simple "free-floating mass" mainly for easiness of exposition
  - other (more complex) mechanical (PHS) system could do the job, also constrained (e.g., ground robots)

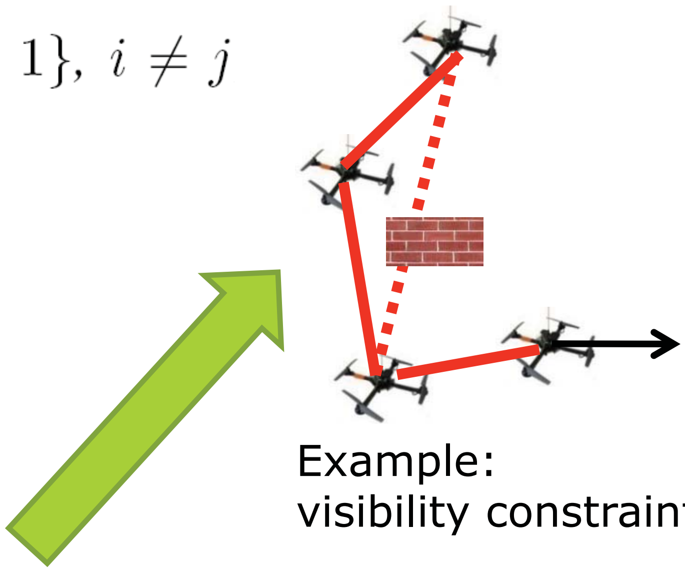
- The Inertia matrix M_i can model different inertial properties in space
  - e.g., a quadrotor UAV with a faster vertical dynamics w.r.t. the horizontal one

- Heterogeneity in the group can be enforced by choosing different M_i and B_i

Neighboring definition

- Let $d_{ij} = \|x_i - x_j\|$ be the interdistance among two agents
- Sensing/communication/interaction range $D \in \mathbb{R}^+$
- Time-varying **neighboring condition** $\sigma_{ij}(t) : \mathbb{R} \rightarrow \{0,\, 1\},\ i \neq j$

$$1)\quad \sigma_{ij}(t) = 0,\ \textit{if}\ d_{ij} > D \in \mathbb{R}^+;$$
$$2)\quad \sigma_{ij}(t) = \sigma_{ji}(t).$$



Example:
visibility constraint

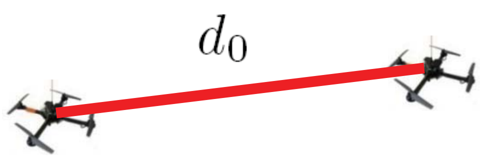
- Interpretation:
  - Must split if too far apart ($d_{ij} > D$)
  - Symmetric neighboring condition
  - Still, can choose to join/split if $d_{ij} \leq D$
    (allow presence of any additional subtask/constraint during motion)
- This relationship induces a time-varying interaction graph $\mathcal{G} = (\mathcal{V},\, \mathcal{E}(t))$ where

$$\mathcal{E}(t) = \{(i,j) \in \mathcal{V} \times \mathcal{V} \,|\, \sigma_{ij}(t) = 1 \Leftrightarrow j \in \mathcal{N}_i\}$$

Agent Interconnection

- When neighbors, the agents should keep a cohesive formation

- We consider the (simple) case of maintaining a desired interdistance $\boxed{0 < d_0 < D}$
  - Other more complex (e.g., relative position) cases are possible



$$\begin{cases} \dot{p}_i = F_i^a + F_i^e - B_i M_i^{-1} p_i \\ v_i = \dfrac{\partial \mathcal{K}_i}{\partial p_i} = M_i^{-1} p_i \end{cases}$$

- This cohesive motion must be achieved by means of local and 1-hop information (decentralization), and by exploiting the coupling force F_i^a in the agent dynamics

- When non-neighbors, no interaction among the agents

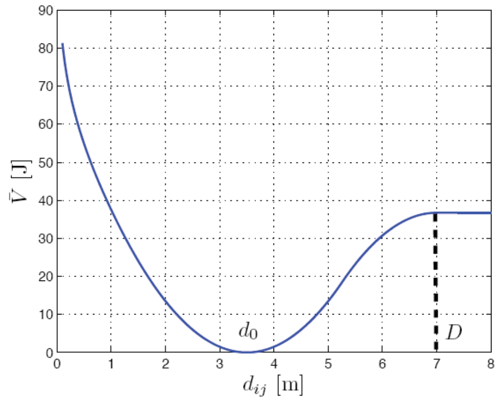
Agent Interconnection

- How to model this interagent coupling? Let us model it as a (nonlinear) elastic element

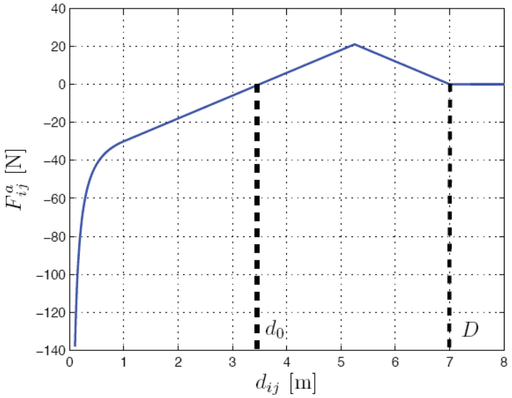
- Let $x_{ij} \in \mathbb{R}^3$ be the state of this element, and $V(x_{ij}) = \bar{V}(\|x_{ij}\|) \geq 0$ some (lower-bounded) Energy function (Hamiltonian)

- Take the usual PHS form for a storing element $\begin{cases} \dot{x}_{ij} = v_{ij} \\ F^a_{ij} = \dfrac{\partial V(x_{ij})}{\partial x_{ij}} \end{cases}$ where $v_{ij},\, F^a_{ij} \in \mathbb{R}^3$ are the input/output vectors

- For $V(x_{ij})$, we take a function
  - lower-bounded
  - with a minimum at d_0
  - becoming flat for $d_{ij} > D$
  - growing unbounded for $d_{ij} \to 0$



$\bar{V}$



F^a_{ij}

Inter-agent interaction

- When i and j are neighbors ($\sigma_{ij}(t) = 1 \Leftrightarrow j \in \mathcal{N}_i$) the elastic element is coupled with the agent dynamics

$$\begin{cases} \dot{p}_i = F_i^a + F_i^e - B_i M_i^{-1} p_i \\ v_i = \frac{\partial \mathcal{K}_i}{\partial p_i} = M_i^{-1} p_i \end{cases}$$

$$\begin{cases} \dot{x}_{ij} = v_{ij} \\ F_{ij}^a = \frac{\partial V(x_{ij})}{\partial x_{ij}} \end{cases}$$

$$\begin{cases} \dot{p}_j = F_j^a + F_j^e - B_j M_j^{-1} p_j \\ v_j = \frac{\partial \mathcal{K}_j}{\partial p_j} = M_j^{-1} p_j \end{cases}$$

- F_i^a can be computed in a decentralized way $F_i^a = \sum_{j \in \mathcal{N}_i} F_{ij}^a := \sum_{j \in \mathcal{N}_i} \frac{\partial \bar{V}}{\partial d_{ij}} \boxed{\frac{\partial d_{ij}}{\partial x_{ij}}}$

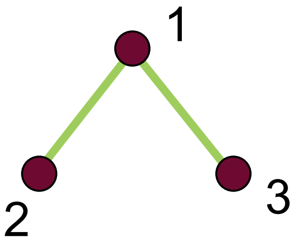
Relative bearing

- When $j \notin \mathcal{N}_i$, the elastic element is disconnected from the agents

Model of the Slave-side

- The overall slave-side in **port-Hamiltonian** (energetic) form can be rewritten as

$$\begin{cases} \begin{pmatrix} \dot{p} \\ \dot{x} \end{pmatrix} = \left[\begin{pmatrix} 0 & \mathcal{I}(t) \\ -\mathcal{I}^T(t) & 0 \end{pmatrix} - \begin{pmatrix} B & 0 \\ 0 & 0 \end{pmatrix} \right] \begin{pmatrix} \frac{\partial H}{\partial p} \\ \frac{\partial H}{\partial x} \end{pmatrix} + GF^e \\ v = G^T \begin{pmatrix} \frac{\partial H}{\partial p} \\ \frac{\partial H}{\partial x} \end{pmatrix} \end{cases}$$



$\boxed{\mathcal{I}(t) = \mathcal{I}_{\mathcal{G}}(t) \otimes I_3}$ and $\mathcal{I}_{\mathcal{G}}(t)$ is the incidence matrix of graph $\mathcal{G}(t)$

$$x = (x_{12}^T, \ldots, x_{1N}^T, x_{23}^T, \ldots, x_{2N}^T, \ldots, x_{N-1N}^T)^T \in \mathbb{R}^{\frac{3N(N-1)}{2}}$$ and

$$p = (p_1^T, \ldots, p_N^T)^T \in \mathbb{R}^{3N}$$

- The total energy (Hamiltonian) of the system is

$$H = \sum_{i=1}^{N} \mathcal{K}_i + \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} V(x_{ij})$$

- For fixed topology $\mathcal{I}(t) = const$, the system is passive $\dot{H} \leq v^T F^e$

Slave passivity

- Prop 1: if the graph topology stays constant $\mathcal{I}(t) = const$, the slave-side is a passive system

$$\dot{H} = \underbrace{\boxed{\begin{pmatrix} \frac{\partial^T H}{\partial p} & \frac{\partial^T H}{\partial x} \end{pmatrix} \begin{pmatrix} 0 & \mathcal{I} \\ -\mathcal{I}^T & 0 \end{pmatrix} \begin{pmatrix} \frac{\partial H}{\partial p} \\ \frac{\partial H}{\partial x} \end{pmatrix}}}_{\text{=0 because of skew-symmetry}} \underbrace{\boxed{- \frac{\partial^T H}{\partial p} B \frac{\partial H}{\partial p}}}_{\text{Negative definite}} + v^T F^e \leq v^T F^e$$

- What about the general case of time-varying $\mathcal{I}(t)$?

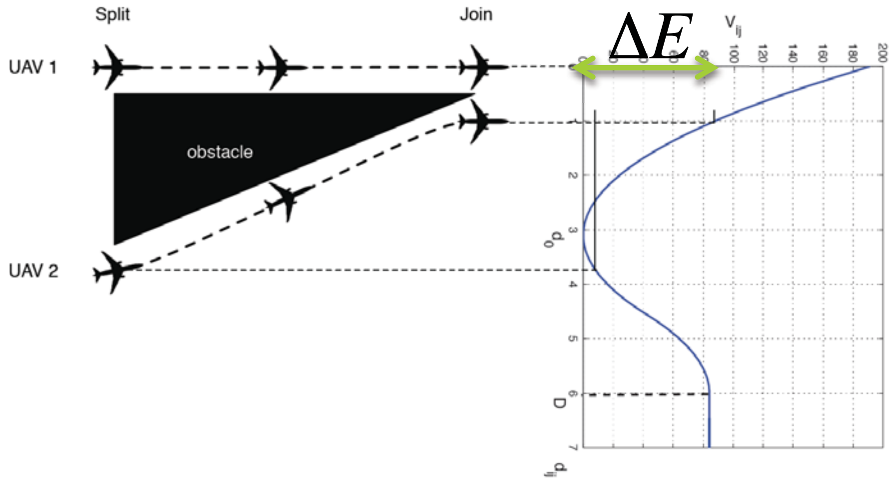
- Prop 2: a split decision $\sigma_{ij} = 1 \rightarrow \sigma_{ij} = 0$ preserves passivity

- Reason: losing an edge induces a new subgraph $\mathcal{G} \rightarrow \mathcal{G}'$ and associated $\mathcal{I} \rightarrow \mathcal{I}'$

- However, the new matrix $\begin{pmatrix} 0 & \mathcal{I}' \\ -\mathcal{I}^{T\prime} & 0 \end{pmatrix}$ will keep being skew-symmetric…

Slave passivity

- A split decision $\sigma_{ij} = 1 \rightarrow \sigma_{ij} = 0$ preserves passivity
- A join decision $\sigma_{ij} = 0 \rightarrow \sigma_{ij} = 1$ **is more involved**
- Reason: different interdistance d_{ij} at the join decision w.r.t. the split decision
- Possible higher energy level $\bar{V}(d_{ij}) \longrightarrow$ creation of "extra" energy



- At the join, the state of the elastic element must be reset to the actual relative position of agents i and j $\quad \boxed{x_{ij} \leftarrow x_i - x_j}$
- This action, in general, **costs extra energy**! (thus, can violate passivity)

Augmented Slave-side

- "**Passify**" the join decisions (cover for the "extra" join energy)

- Idea: because of local damping B_i , every agent dissipates some power

$$D_i = p_i^T M_i^{-T} B_i M_i^{-1} p_i$$

- Store this power in a local variable called energy **tank** $t_i \in \mathbb{R}$
  with energy function $T_i = \frac{1}{2} t_i^2$

- Exploit the Tank Energies (in a decentralized way) to cover for passivity violations

- Bottom-line: keeping track of the dissipated energy grants a "passivity margin" to be freely used for implementing generic actions in a passive way

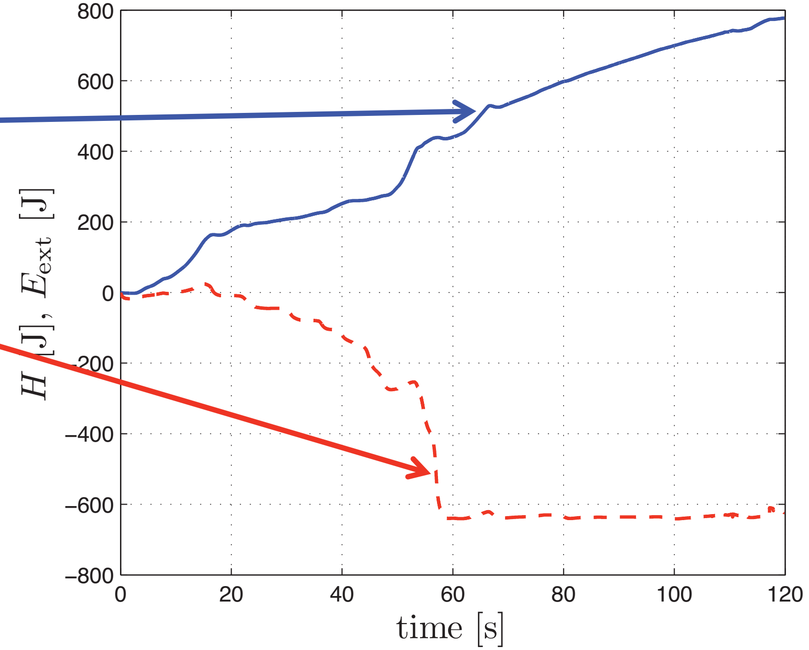
Energy Tanks

- In its integral form, the passivity condition reads

$$H(t) - H(t_0) = \int_{t_0}^{t} y^T u \, \mathrm{d}\tau - \underbrace{\int_{t_0}^{t} \frac{\partial H^T}{\partial x} R(x) \frac{\partial H}{\partial x} \mathrm{d}\tau}_{\leq 0}$$

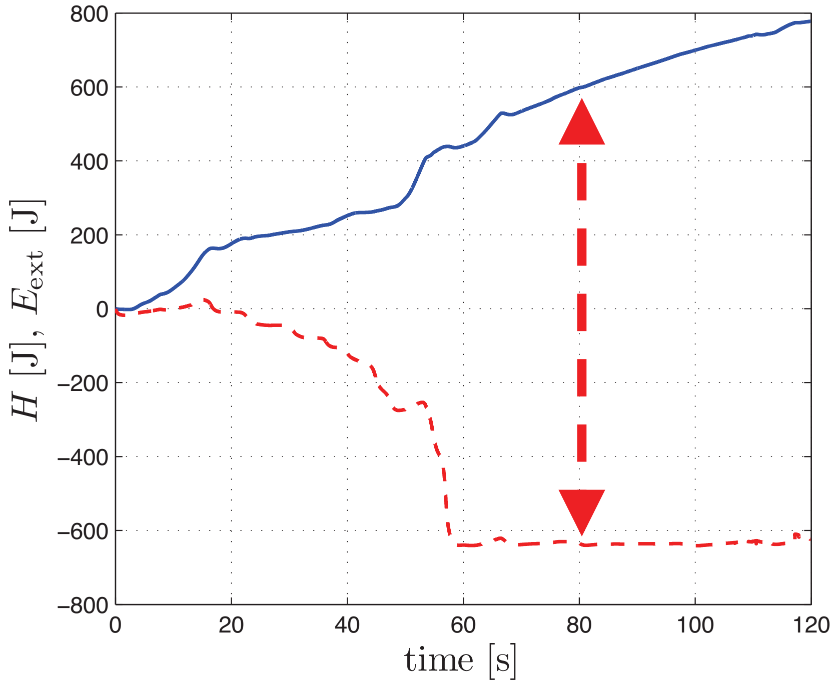
- Let $E_{\text{in}}(t) = H(t) - H(t_0)$ and $E_{\text{ext}}(t) = \int_{t_0}^{t} y^T u \, \mathrm{d}\tau$

- Over time, $E_{\text{in}}(t) \leq E_{\text{ext}}(t)$



Energy Tanks

- Over time, a gap between $E_{\text{ext}}(t)$ and $E_{\text{in}}(t)$



- Because of the integral of the dissipation term

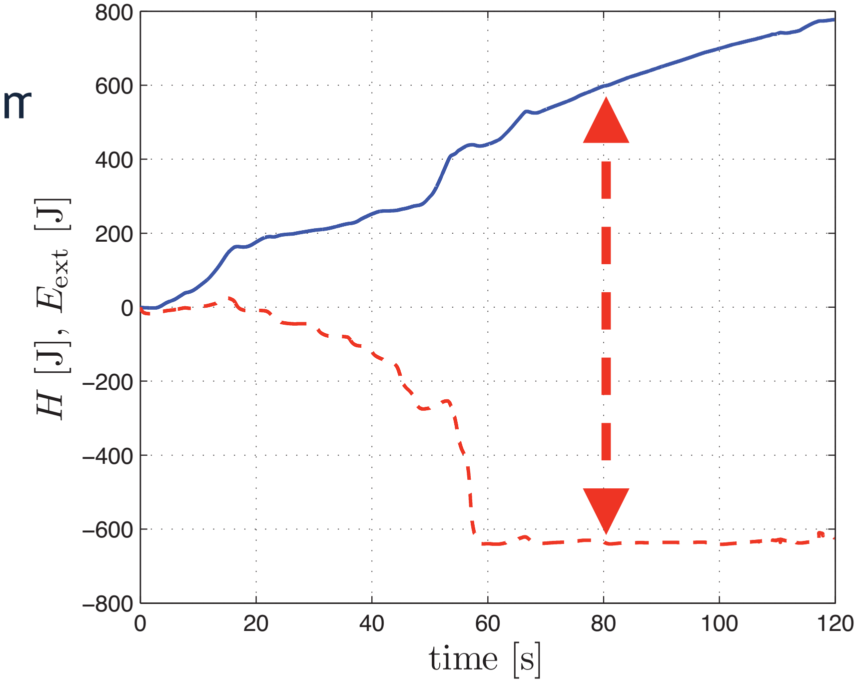
$$H(t) - H(t_0) = \int_{t_0}^{t} y^T u \, \mathrm{d}\tau \underbrace{- \int_{t_0}^{t} \frac{\partial H^T}{\partial x} R(x) \frac{\partial H}{\partial x} \mathrm{d}\tau}_{\leq 0}$$

- However, we would be happy (from the passivity point of view) by just ensuring a lossless energy balance

$$H(t) - H(t_0) = \int_{t_0}^{t} y^T u \, \mathrm{d}t \iff E_{\text{in}}(t) = E_{\text{ext}}(t)$$

Energy Tanks

- Dissipation term: passivity margin of the system
- Imagine we could recover this "passivity gap"
- This recovered energy can be freely used for whatever goal **without violating the passivity constraint**



- This idea is at the basis of the Energy Tank machinery
- Energy Tank: an energy storing element with state $x_t \in \mathbb{R}$ and energy function

$$T(x_t) = \frac{1}{2}x_t^2 \geq 0$$

$$\begin{cases} \dot{x}_t & = & u_t \\ y_t & = & \dfrac{\partial T}{\partial x_t}(= x_t) \end{cases}$$

Passivity of the Group

- Strategy for implementing a join decision in a passive way among agents $(i,\, j)$:
  - 1. at the join moment, compute $\Delta V = V(x_i - x_j) - V(x_{ij})$
  - 2. if $\Delta V \leq 0$, implement the join (and store ΔV back into the tanks T_i and T_j)
  - 3. if $\Delta V > 0$, extract ΔV from T_i and T_j

- **What if $T_i + T_j < \Delta V$?**

- Must take a decision:
  - Do not join (and wait for better conditions)
  - Ask the rest of the group for "help"

- How to ask for "help" in a decentralized and passive way?
  - <u>**A possibility**</u>: run a <u>**consensus**</u> on all the Tank Energies
  - This redistributes the energies within the group
  - But it doesn't change the total amount of energy

Passivity of the Group

- Compact form of the Passive Join procedure (decentralized and passive)

Procedure PassiveJoin

Data: $x_i, x_j, x_{ij}^s, t_i, t_j$

1 *Compute* $\Delta E = V(x_i - x_j) - V(x_{ij}^s)$;

2 **if** $\Delta E \leq 0$ **then**

3   *Store* $(-\Delta E)/2$ in the tank through input w_{ij};

else

4   **if** $T_i(t_i) + T_j(t_j) < \Delta E + 2\varepsilon$ **then**

5   Run a *consensus* on the tank variables;

6   **if** $2T_i(t_i) < \Delta E + 2\varepsilon$ **then**

7   *Dampen* until $T(t_i) + T(t_j) \geq \Delta E + 2\varepsilon$;

8   *Extract* $\dfrac{T(t_i)}{T(t_i) + T(t_j)}\Delta E$ from the tank through input w_{ij};

9 *Join*;

- Note: if after the consensus still not enough energy (line 6)
  - The agents do not join
  - They can switch to a high damping mode for more quickly refilling the Tanks

Passivity of the Group

- Additional remarks:

- We can always enforce a limiting strategy for the Tank refilling action by means of a parameter $\alpha_i \in \{0,\ 1\}$

$$\begin{cases} \dot{p}_i &= F_i^a + F_i^e - B_i M_i^{-1} p_i \\ \dot{x}_{t_i} &= \boxed{\alpha_i} \dfrac{1}{x_{t_i}} D_i + \sum_{j=1}^{N} w_{ij}^t \\ y &= \begin{bmatrix} v_i \\ x_{t_i} \end{bmatrix} \end{cases}$$

such that $\alpha_i = \begin{cases} 0, & \text{if} \quad T_i \geq \bar{T}_i \\ 1, & \text{if} \quad T_i < \bar{T}_i \end{cases}$ where $\bar{T}_i$ is a suitable upper bound for the Tank energy level

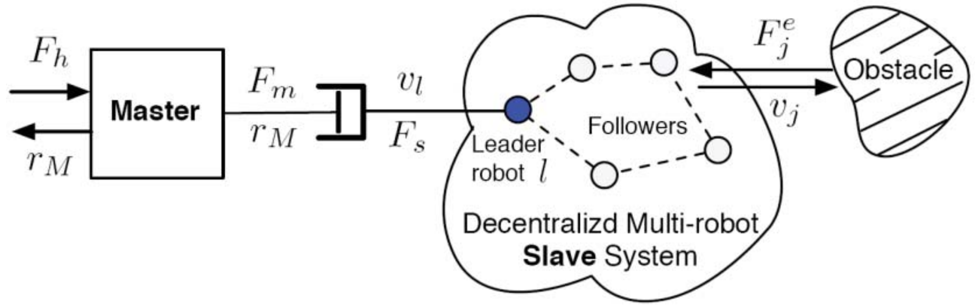
- This way, we can avoid a too large accumulation and prevent **practical** non-passive behaviors over short periods of time

Bilateral Teleoperation of Multiple UAVs

- Consider one leader, and split its external force as $F_l^e = F_s + F_l^{\text{env}}$

- Interconnect master and leader in this (passive) way

$$\begin{cases} \boxed{F_s = b_T(r_M - v_l)} \\ F_m = -b_T(r_M - v_l) \end{cases}, \quad b_T > 0$$

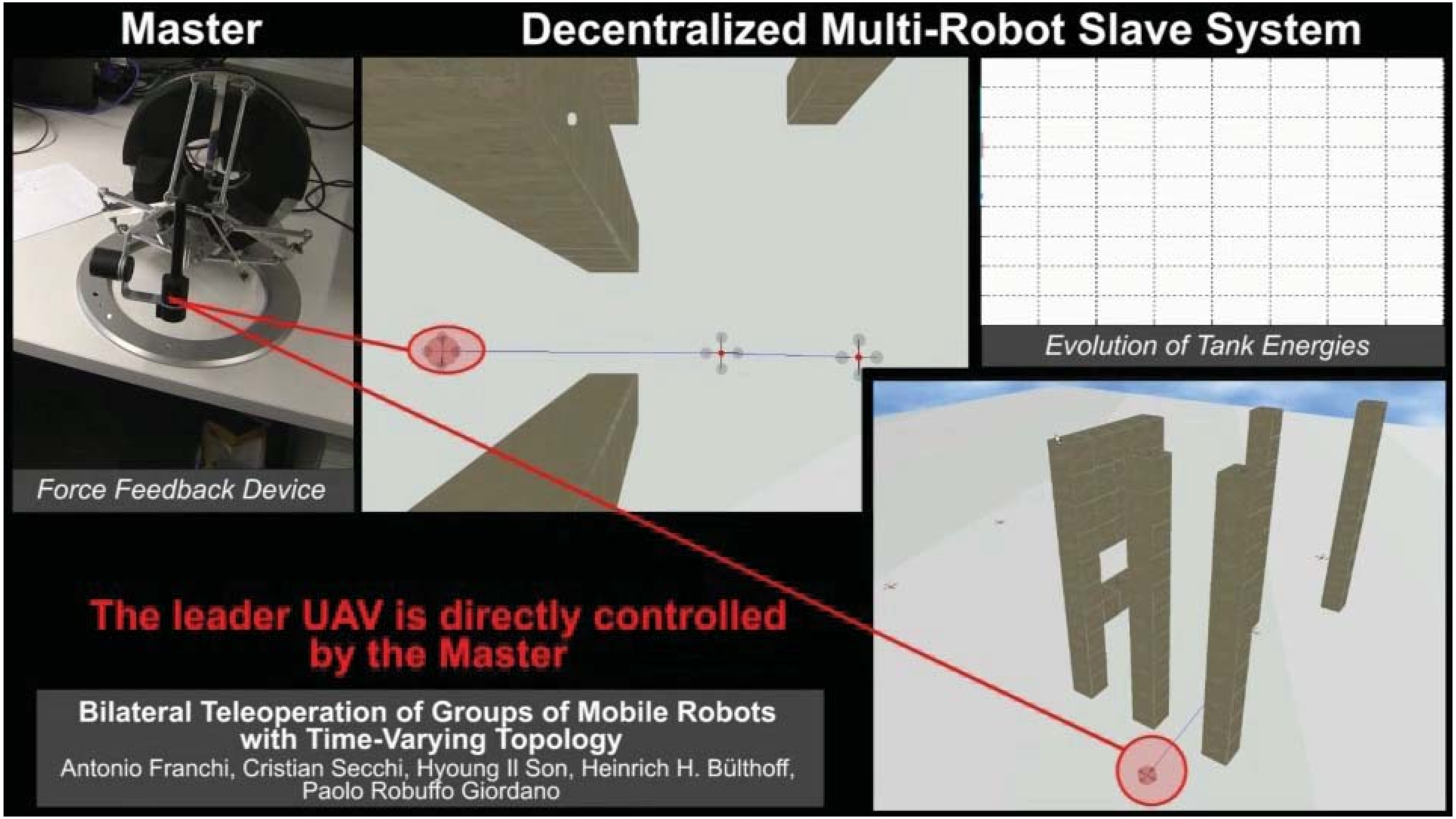


- v_l is the leader velocity
- r_M is (almost) the master position

- Force F_m will inform about the mismatch $v_l - r_M$
  - Number of agents in the connected component of the leader (their total inertia)
  - Absolute speed of the group
  - Interaction with the environment (obstacles)

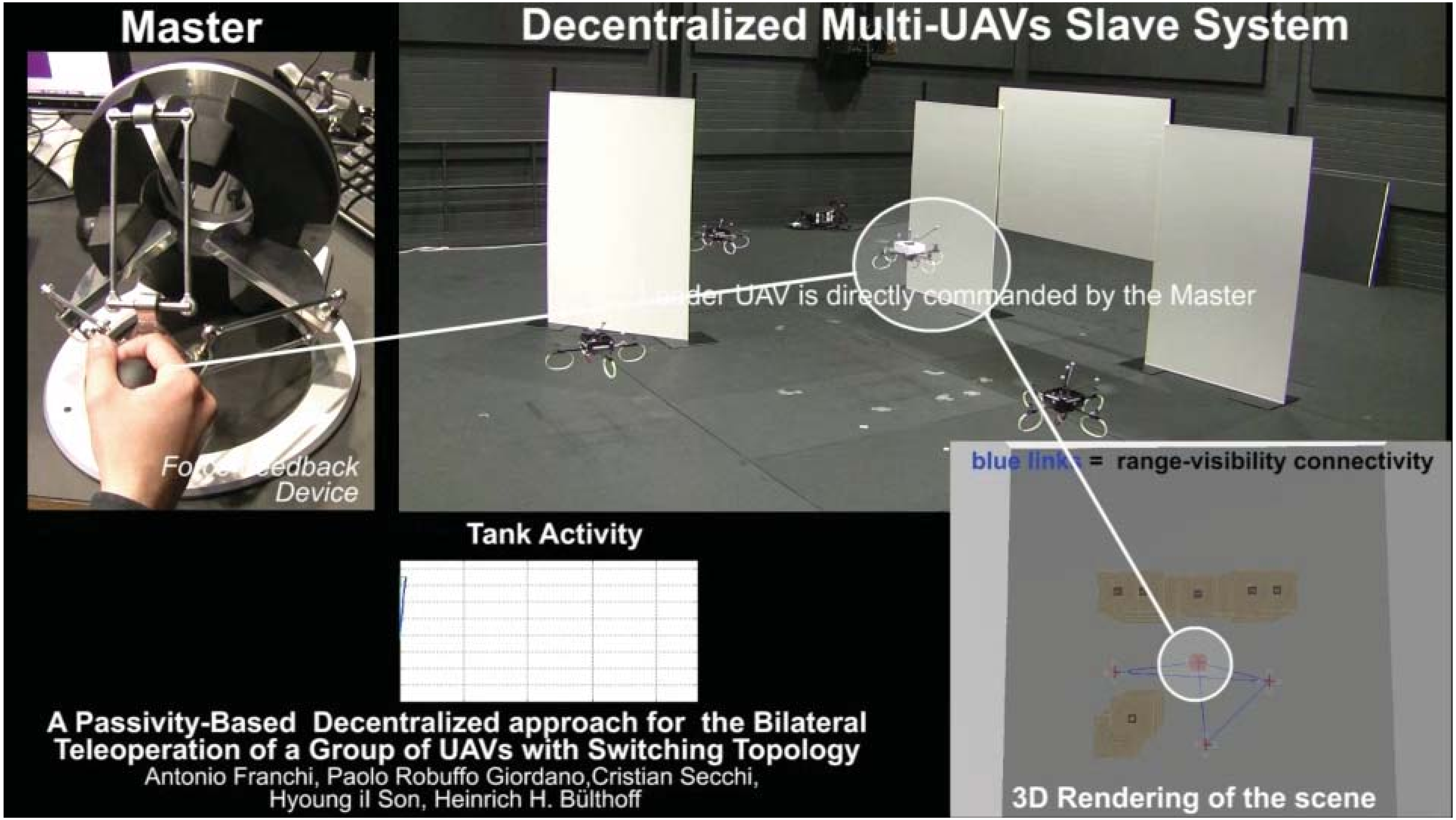
- Obstacles are considered as passive systems producing repulsive forces (spring-like elements)

Bilateral Teleoperation of Multiple UAVs



ICRA 2011, T-RO 2012 (to appear)

Bilateral Teleoperation of Multiple UAVs



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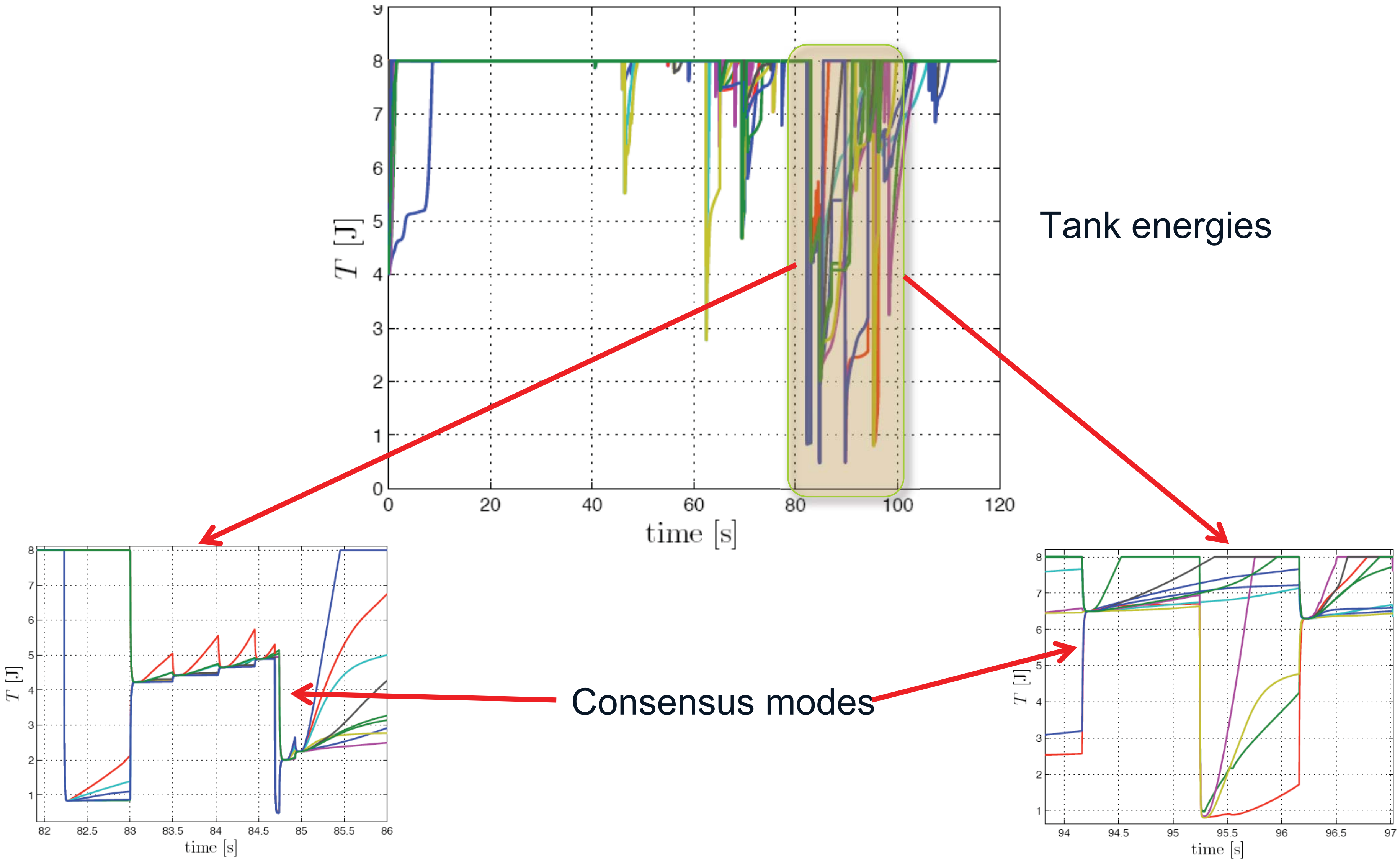
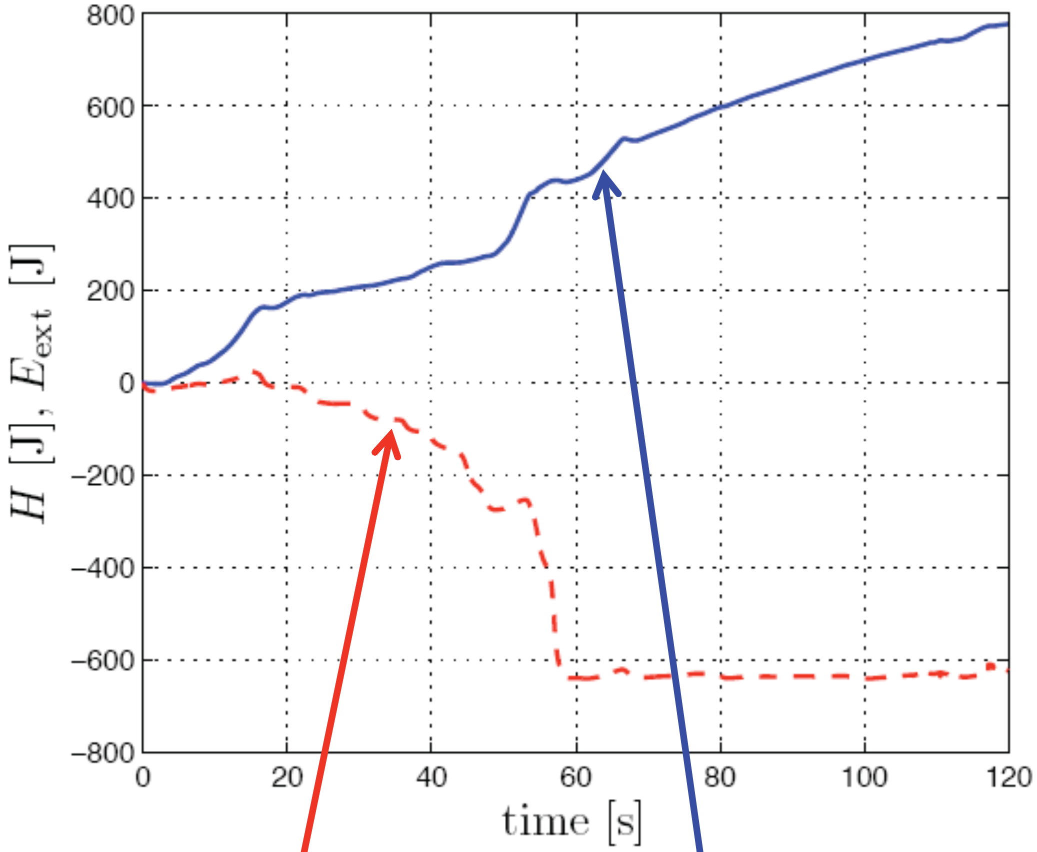
Bilateral Teleoperation of Multiple UAVs



Bilateral Teleoperation of Multiple UAVs



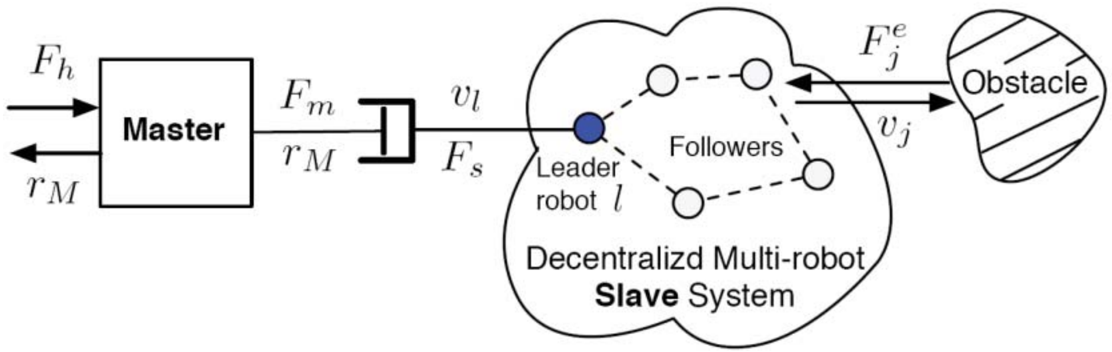
Slave-side Passivity condition

$$\mathcal{H}(t) - \mathcal{H}(t_0) \leq \int_{t_0}^{t} v^T(\tau) F^e(\tau) \mathrm{d}\tau$$

(Integral version of $\dot{\mathcal{H}} \leq v^T F^e$)

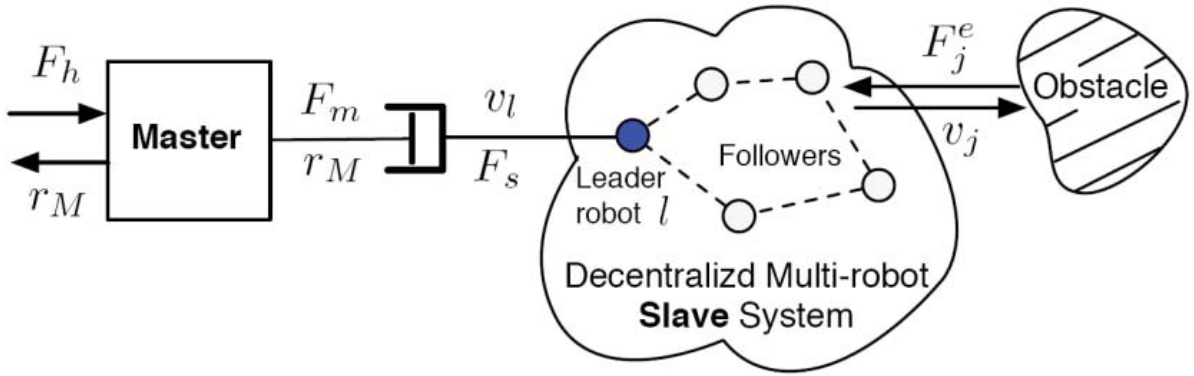
Intermezzo

- Where does the energy to keep everything in motion come from?
- As the agents move, they necessarily dissipate energy (damping terms)
- The dissipated energy is stored back into the Tank but then still used to implement joins
- If the slave-side had started with some initial energy $\mathcal{H}(t_0)$, this will be eventually dissipated because of local damping or join maneuvers
- Hence, "**new energy**" can only be supplied by the "**Master-side**"



Intermezzo

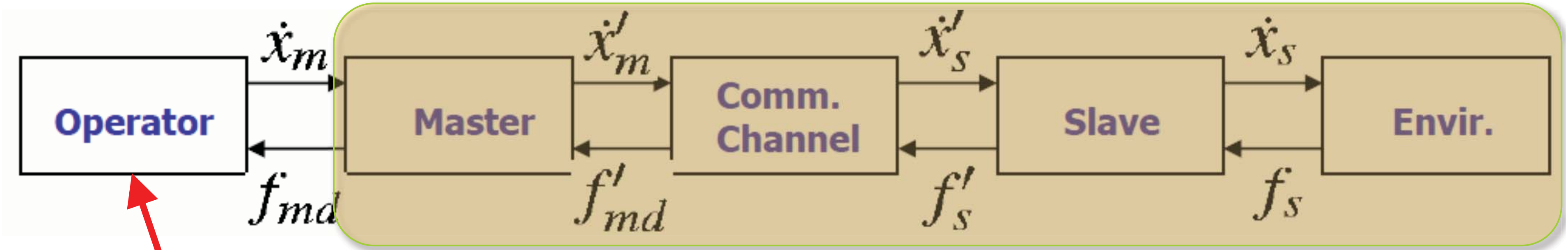
- However, the master is also assumed to be a passive system
- It can have some initial energy, but cannot create energy over time either
- At some point, its internal energy storage will also be depleted



- So, where does the energy to keep everything in motion (for a sustained amount of time) come from?

Intermezzo

- <u>**It ultimately comes from the Human operator!**</u>



Passive system!
On its own, can only “lose energy” over time…

The human operator acts on the master
To move the master, he/she must perform (mechanical) work
This work is the source of energy that keeps everything motion

Passivity Metaphor = as in life, <u>nothing comes for free</u>, to get something done one must <u>work hard</u> and put in a lot of <u>(his/her) energy</u>

Velocity Synchronization

- Assume a constant velocity command for the leader $r_M = const$
- We are interested in characterizing the (possible) steady-state synchronization with this velocity command

$$v_i \to r_M, \quad \forall i \ ?$$

- Characterization of the steady-state of the system (**if it exists**)
- Assumptions for the steady-state:
  - 1) $F_i^{\text{env}} = 0, \quad \forall i = 1, \ldots, N$ (no environmental forces ~ no close obstacles)
  - 2) Tanks are full to $\bar{T}_i$ and $\Gamma = 0$ (no joins, no energy exchanges with elastic elements)
  - 3) $\mathcal{G}$ is **connected** (can always reduce to the connected component of the leader)
- Also assume (w.l.o.g.) that the leader is agent 1
  - For the leader, $F_1^e = F_s = b_T(r_M - v_1)$
  - For all the others, $F_i^e = F_i^{\text{env}} = 0$ (because of Assumption 1)

Velocity Synchronization

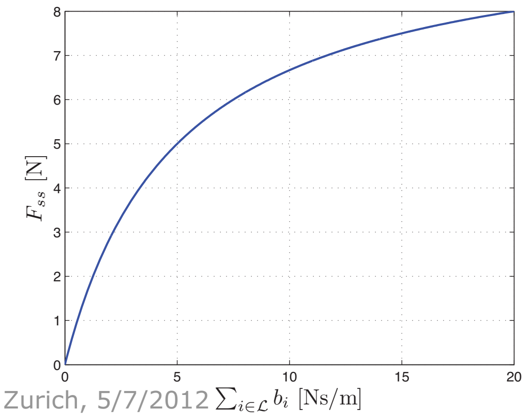
- Result: at steady-state $v_i \to v_{ss} = (\mathbf{1}_{N_3}^T B' \mathbf{1}_{N_3})^{-1} b_T r_M$

- As illustration, for "scalar" damping terms $B_i = b_i I_3$ everything reduces to

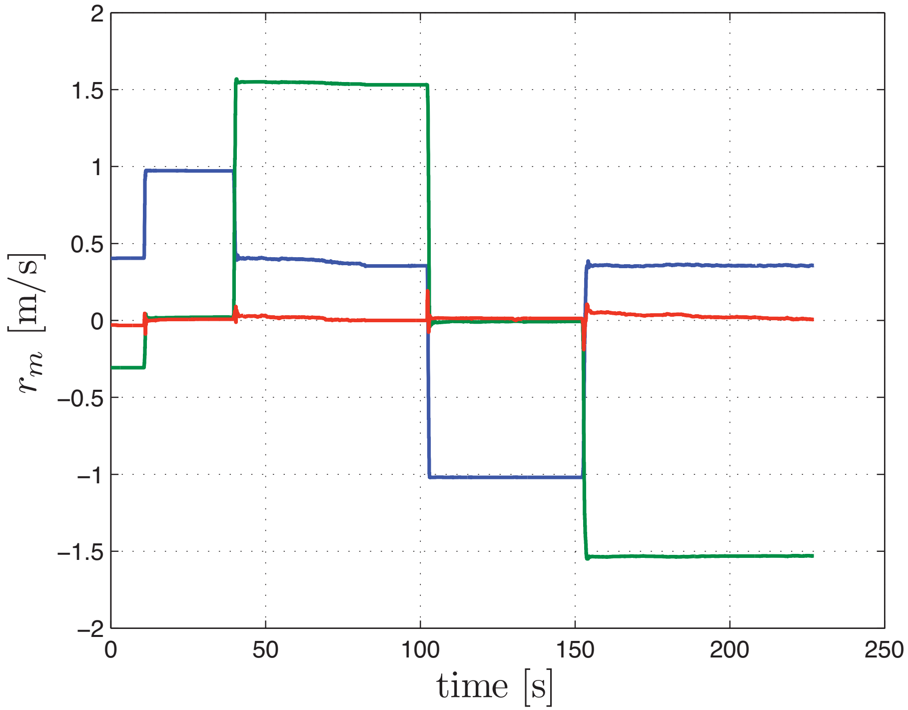
$$v_{ss} = \frac{b_T r_M}{b_T + \sum b_i} \qquad\qquad F_{ss} = \frac{b_T K r_M \sum b_i}{b_T + \sum b_i}$$

- Perfect synchronization only in the hypothetical situation $b_i = 0$ (no damping on any agent!)
    - In this case, $v_{ss} = r_M$ and $F_{ss} = 0$

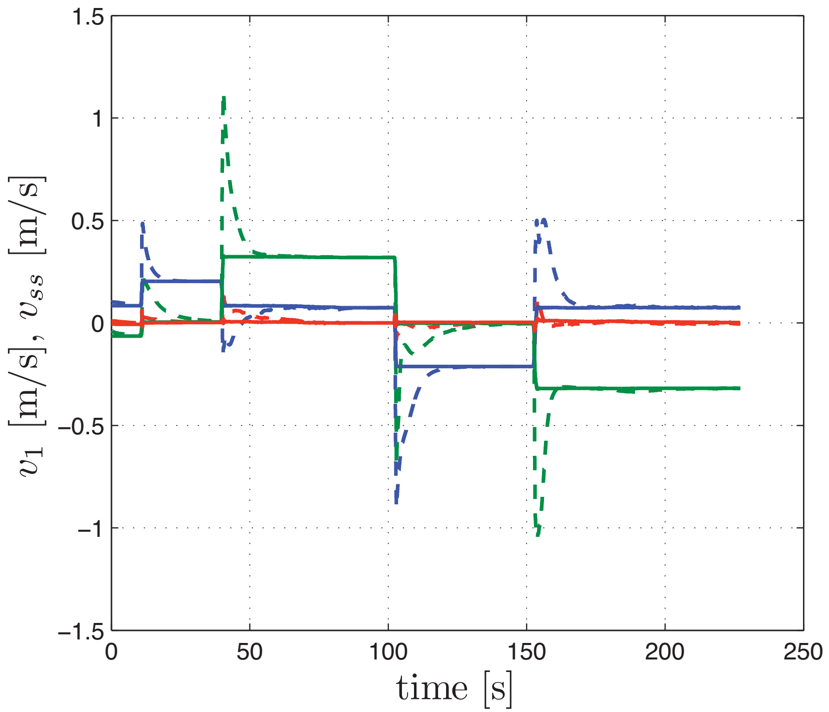
- In general, the force F_{ss} carries information about the group absolute speed and total number agents



Velocity Synchronization

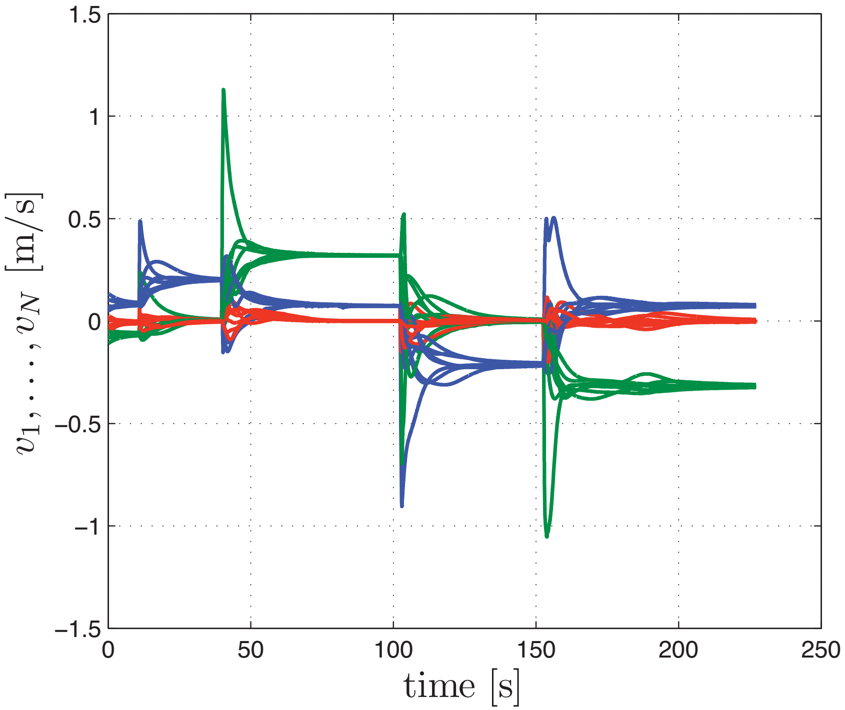


Leader velocity command r_M

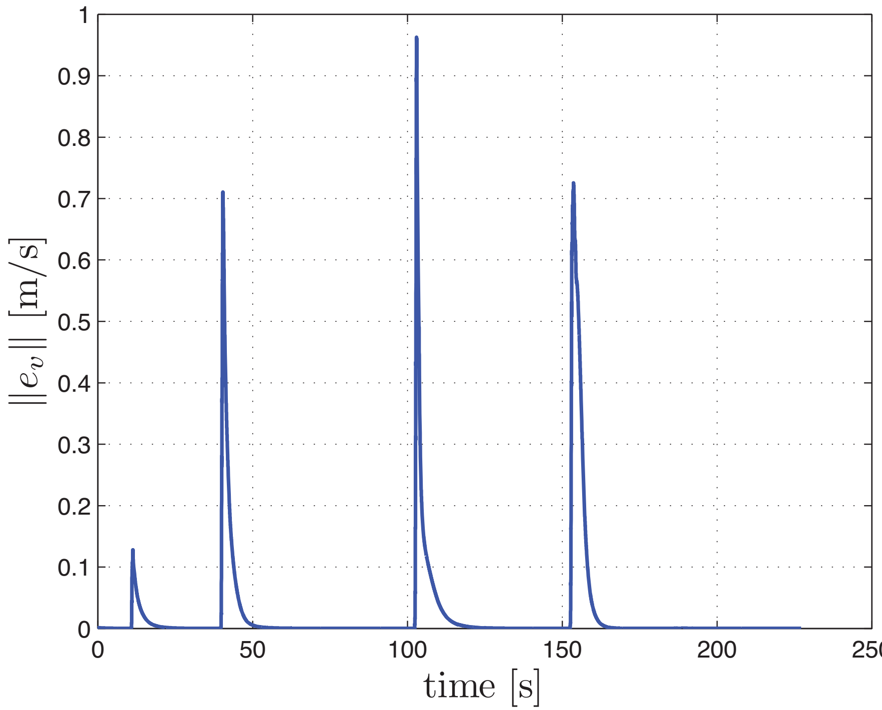


Leader vel. v_1 vs. predicted v_{ss}

Velocity Synchronization



All agent velocities



Norm of velocity synchronization error

$$\|e_v\| = \|v - \mathbf{1}_{N_3} v_{ss}\|$$

Velocity Synchronization

- A (decentralized) extension to synchronize velocities with r_M at steady-state
- The damping terms B_i are
  - good for stabilization and Tank refill
  - bad for vel. synchronization, as they "slow down" the agents….
  - ….it seems they should be "switched off"
- Idea: modify the agent dynamics, considering

$$\begin{cases} \dot{p}_i &= F_i^a + F_i^e - B_i M_i^{-1} p_i \\ \dot{x}_{t_i} &= \frac{1}{x_{t_i}} D_i + \sum_{j=1}^N w_{ij}^t \\ y &= \begin{bmatrix} v_i \\ x_{t_i} \end{bmatrix} \end{cases} \Rightarrow \begin{cases} \dot{p}_i &= F_i^a + F_i^e + F_i^s + F_i^d \\ \dot{x}_{t_i} &= \frac{1}{x_{t_i}} D_i + \sum_{j=1}^N w_{ij}^t \\ y &= \begin{bmatrix} v_i \\ x_{t_i} \end{bmatrix} \end{cases}$$

where $F_i^d = -B_i(t_i) M_i^{-1} p_i$ is the "damping" force, but with a **variable damping term**

$$\boxed{B_i(t_i) = \begin{cases} 0 & \text{if} \quad T(t_i) = \bar{T}_i \\ \bar{B}_i & \text{if} \quad T(t_i) < \bar{T}_i \end{cases}}$$

Velocity Synchronization

- The damping B_i is now active only when needed to refill the Tank T_i

$$\begin{cases} \dot{p}_i &= F_i^a + F_i^e + F_i^s + F_i^d \\ \dot{x}_{t_i} &= \dfrac{1}{x_{t_i}} D_i + \sum_{j=1}^{N} w_{ij}^t \\ y &= \begin{bmatrix} v_i \\ x_{t_i} \end{bmatrix} \end{cases}$$

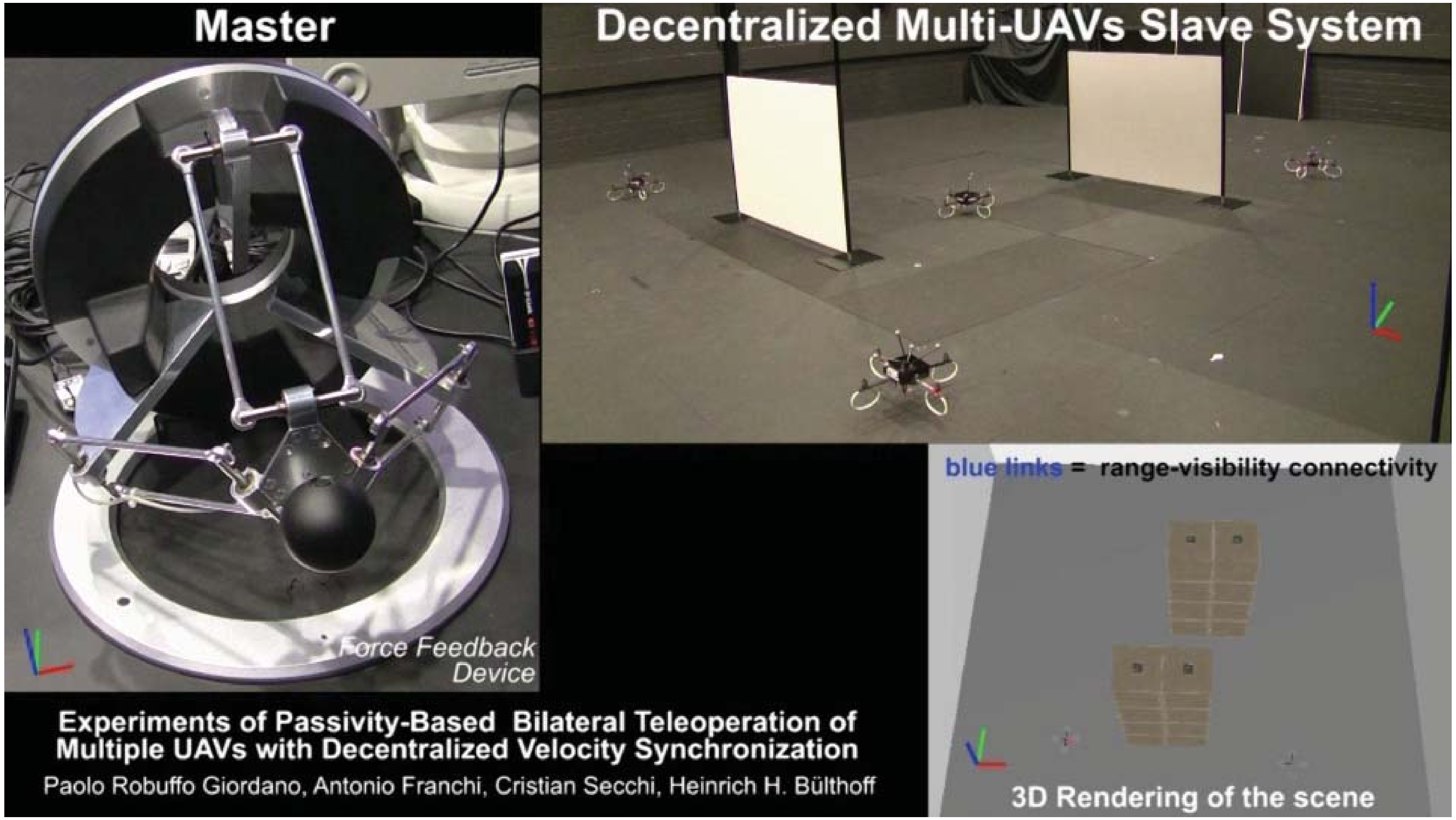
- The additional (synchronization) force F_i^s is designed as $F_i^s = -b \sum_{j \in \mathcal{N}_i} (v_i - v_j)$ (<u>consensus among velocities</u>)

- The group dynamics takes the form, with $\mathcal{L} = bL \otimes I_3$

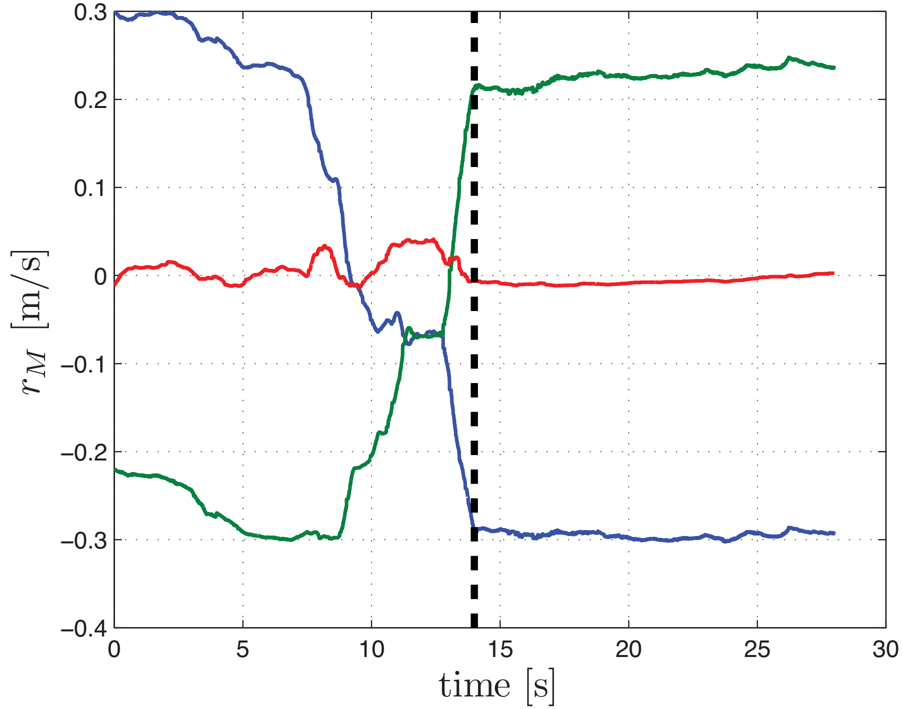
$$\begin{cases} \begin{pmatrix} \dot{p} \\ \dot{x} \\ \dot{t} \end{pmatrix} = \left[\begin{pmatrix} 0 & E & 0 \\ -E^T & 0 & \Gamma^T \\ 0 & -\Gamma & 0 \end{pmatrix} - \begin{pmatrix} \mathcal{L} + B & 0 & 0 \\ 0 & 0 & 0 \\ -PB & 0 & 0 \end{pmatrix} \right] \nabla \mathcal{H} + G F^e \\ v = G^T \nabla \mathcal{H} \end{cases}$$

Velocity Synchronization

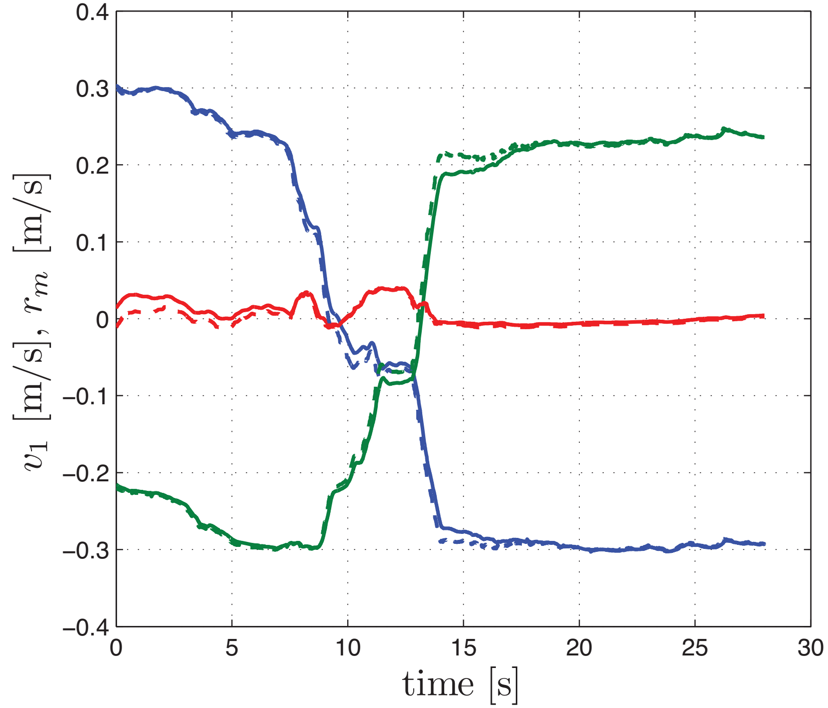
- With the same Assumptions as before (constant commands, Tanks full and connected Graph), it is possible to show that
    - there exists a steady-state $(\dot{p},\, \dot{x},\, \dot{t}) = (0,\, 0,\, 0)$
    - the agents synchronize with the commanded velocity $v = \mathbf{1}_{N_3} r_M$
    - resulting in a null force for the human operator $F_h = F_{ss} = 0$



Velocity Synchronization

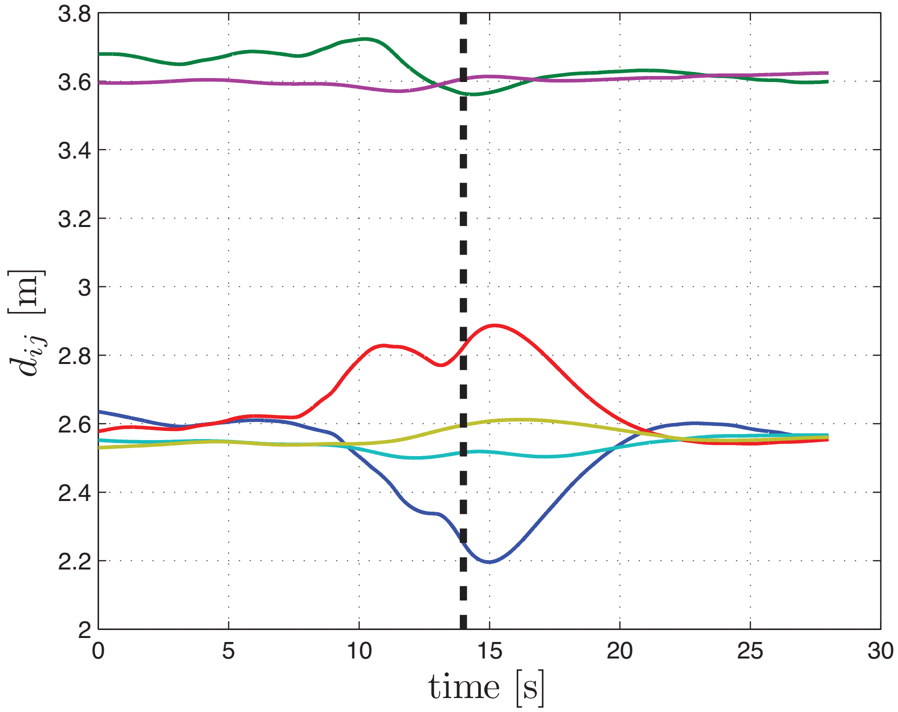


Master velocity commands r_M

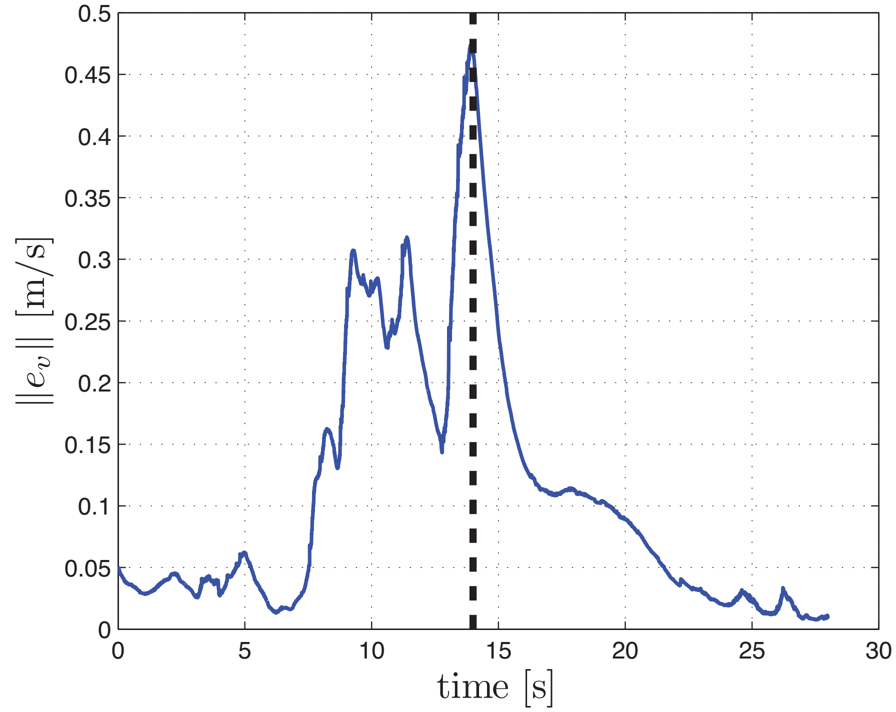


Leader vel. v_1 vs. r_M

Velocity Synchronization



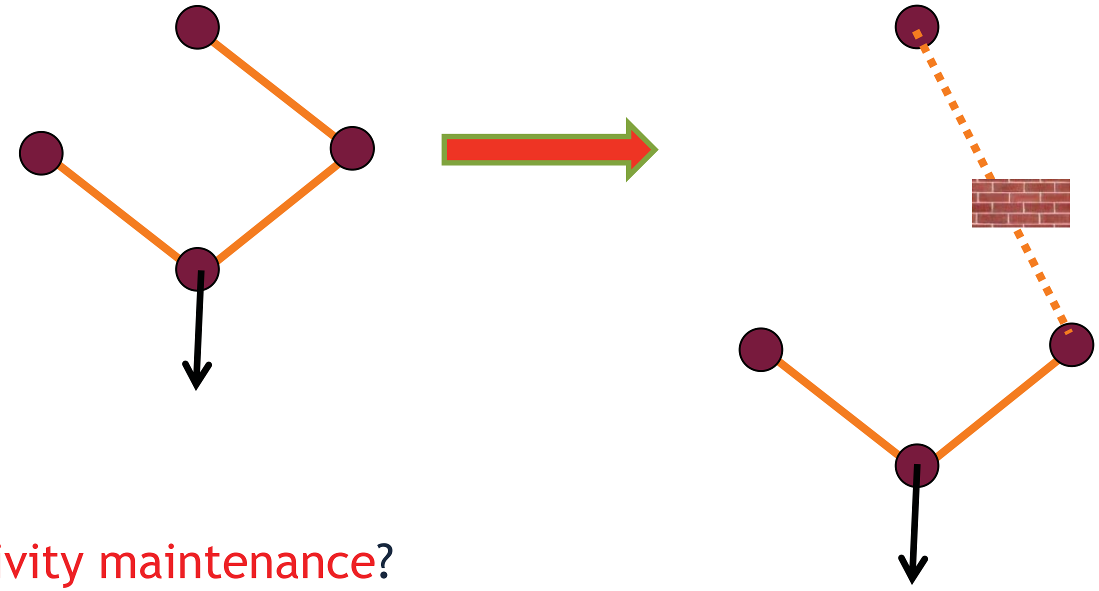
Interdistances



Norm of velocity synchronization error

$$\|e_v\| = \|v - \mathbf{1}_{N_3} r_M\|$$

Connectivity Maintenance



- What about connectivity maintenance?

- Can the graph $\mathcal{G}$ stay connected while still allowing **arbitrary split** and **join** as before?

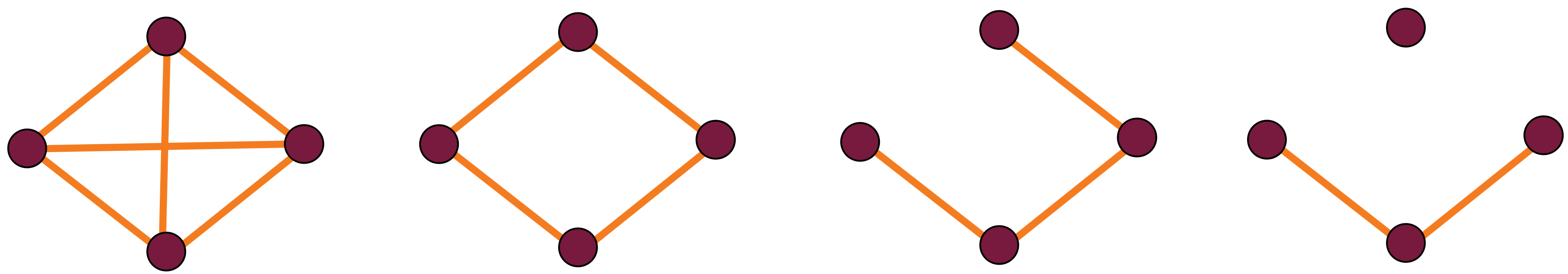
- And…

- How to do it in a decentralized and stable/passive way?

Connectivity Maintenance

- Connected graph -> $\lambda_2 > 0$ (second smallest eigenvalue of the graph Laplacian L)

- λ_2 is a measure of the degree of connectivity in a graph
  - The larger its value, the "more connected" the graph



$\lambda_2 = 4$ $\lambda_2 = 2$ $\lambda_2 = 0.58$ $\lambda_2 = 0$

- However:
  - λ_2 is a global quantity $\longrightarrow$ against decentralization?
  - λ_2 does not vary smoothly over time $\longrightarrow$ cannot take "derivatives"

Connectivity Maintenance

- Idea: design the weights of the Adjacency matrix are smooth functions of the state $A_{ij} = A_{ij}(x) \geq 0$ rather than as discrete quantities $A_{ij} = \{0,\ 1\}$

- Then, the Laplacian itself becomes a smooth function of the state

$$\boxed{L = \Delta(x) - A(x) = L(x)}$$

- Then, one conceive a gradient-like control action $u = \dfrac{\partial \lambda_2}{\partial x}$ based on $\lambda_2 = \lambda_2(x)$

- This gradient has a closed-form expression (Yang, Freeman, Gordon, Lynch, Srinivasa, Sukthankar, "Decentralized estimation and control of graph connectivity for mobile sensor networks", Automatica 2010)

$$\frac{\partial \lambda_2}{\partial x_i} = \sum_{j \in \mathcal{N}_i} \frac{\partial A_{ij}}{\partial x_i} (v_{2_i} - v_{2_j})^2$$

where v_2 is the eigenvector associated to λ_2

Connectivity Maintenance

- How to exploit the freedom in designing the weights $A_{ij}(x)$?

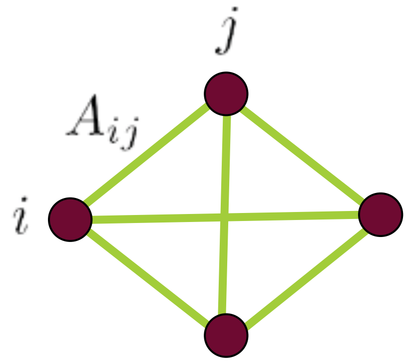
- Typically, weights $A_{ij}(x)$ are chosen to take into account presence of physical limitations for interacting (sensing model as occlusions, maximum range)
  - example: letting $A_{ij}(x_i - x_j) \to 0$ as $d_{ij} \to D$

- Keeping $\lambda_2(x) > 0$ during motion ensures connectivity maintenance w.r.t. such sensing/communication limitations

- We extend this idea to also embed into the weights $A_{ij}(x)$
  - additional agent requirements which should be preferably met (e.g., keeping a desired interdistance)
  - additional agent requirements which must be necessarily met (avoiding collisions with obstacles and other agents)

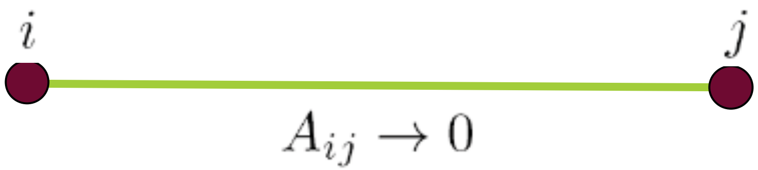
- Everything achieved by the sole "maximization" of the unique scalar quantity $\lambda_2(x)$
  - **"physical" connectivity** + any **additional group requirement**

Connectivity Maintenance

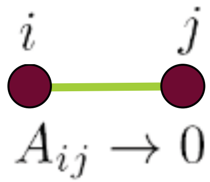


- Idea: have the weights A_{ij} of the adjacency matrix to be smooth functions of the agent states

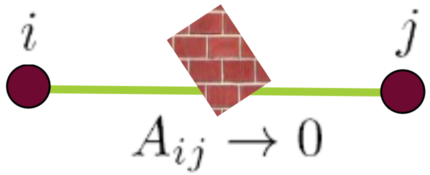
- Let $A_{ij} \to 0$ as any of these conditions are met
  - get too far apart ($> D$)



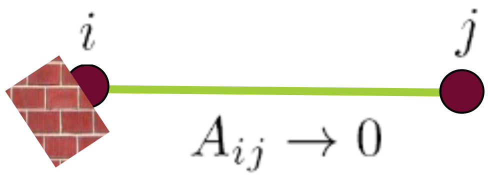
  - get too close (inter-agent collisions)



  - occluded line-of-sight



  - obstacle collision



Connectivity Maintenance

- Define the weights A_{ij} as the product of three terms

$$\boxed{A_{ij} = \alpha_{ij}\beta_{ij}\gamma_{ij}}$$

  - $\gamma_{ij} \to 0$ (and then $A_{ij} \to 0$) if a sensing/communication limitation is approached
    - Edge $(i,\ j)$ will be lost and λ_2 will decrease
    - in our case: exceeding maximum range and occluded line-of-sight

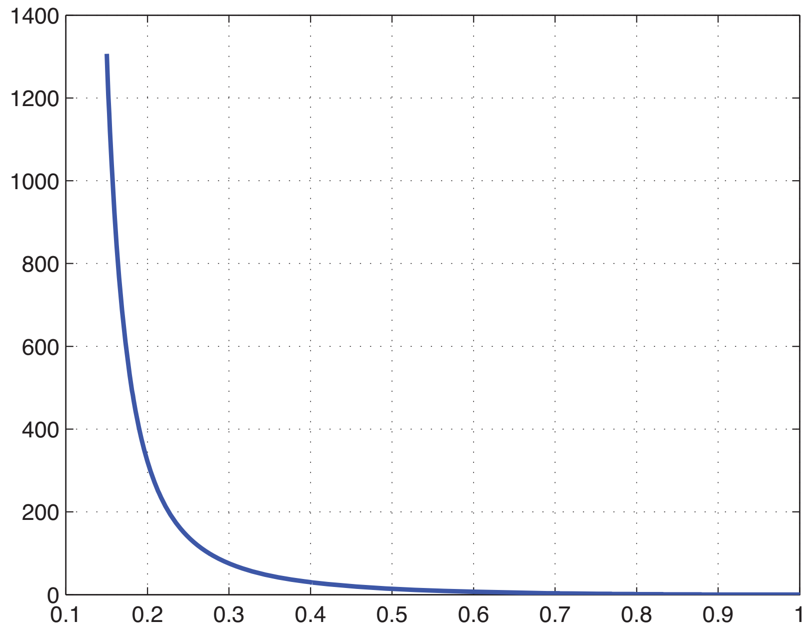
  - $\beta_{ij} \to 0$ (and then $A_{ij} \to 0$) if a “soft requirement” is not met
    - Edge $(i,\ j)$ will be lost and λ_2 will decrease
    - in our case: deviating from a preferred interdistance d_0

  - $\alpha_{ij} \to 0$ (and then $A_{ij} \to 0,\ \forall j$) if a “hard requirement” is not met
    - All edges departing from i will be lost and $\boxed{\lambda_2 \to 0}$
    - in our case: colliding with obstacles and other agents

- Keeping $\lambda_2(x) > 0$ will fulfill these requirements but still allow complete freedom for arbitrary join/split decisions! (as long as $\mathcal{G}$ stays connected)

Connectivity Maintenance

- As final step, we define a Connectivity Potential function $V^\lambda(\lambda_2) \geq 0$ which
  - vanishes for $\lambda_2 \to \lambda_2^{\max}$
  - grows unbounded for $\lambda_2 \to \lambda_2^{\min} < \lambda_2^{\max}$



- This will be the "Elastic Potential Energy" of the system

- Its anti-gradient (connectivity force) w.r.t. the i-th agent position is

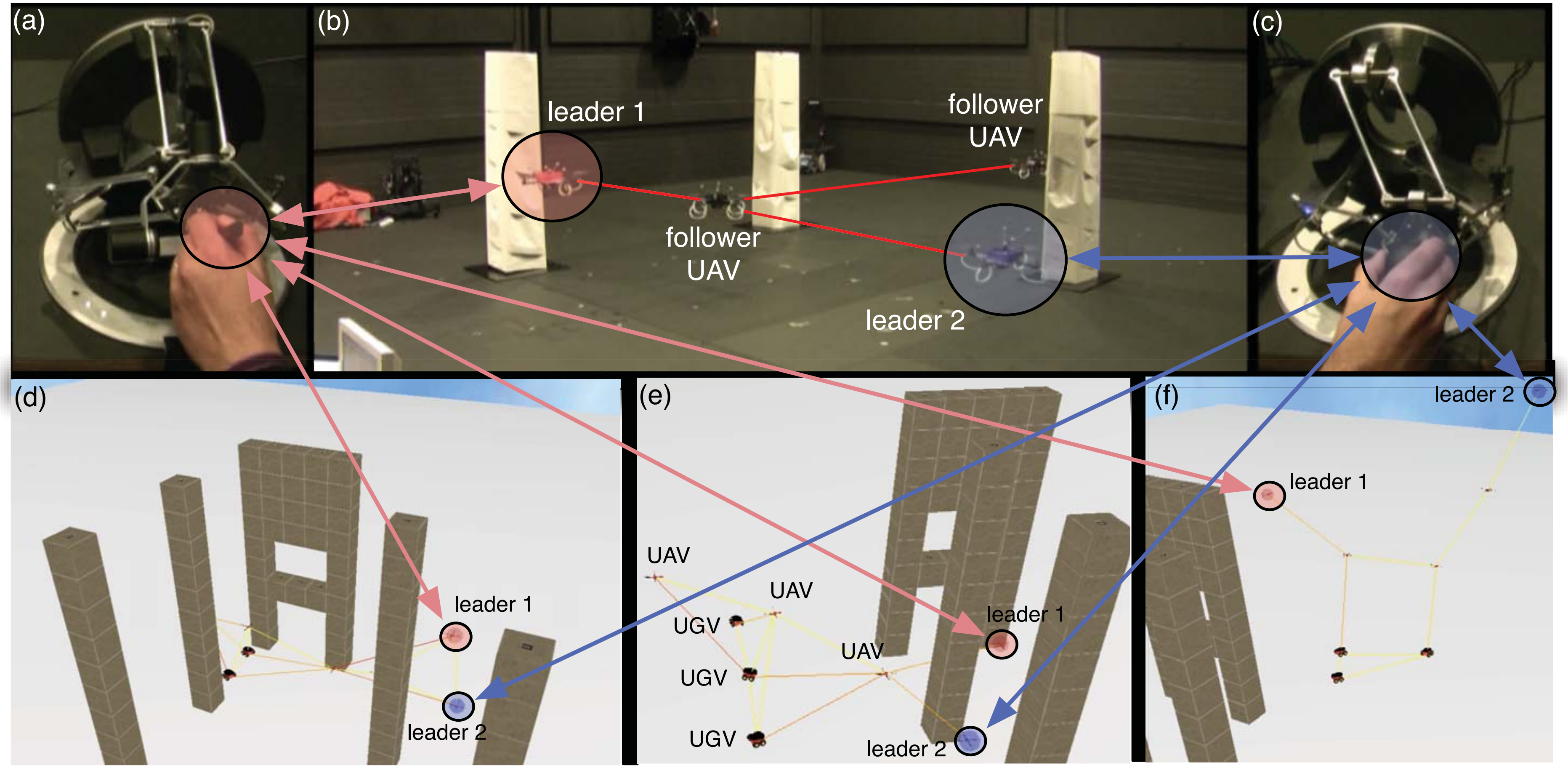
$$F_i^\lambda = -\frac{\partial V^\lambda(\lambda_2(x))}{\partial x_i} = -\frac{\partial V^\lambda(\lambda_2)}{\partial \lambda_2}\frac{\partial \lambda_2(x)}{\partial x_i}$$

- This can be shown to possess the following features:
  - full decentralized evaluation (only local and 1-hop information, complexity per neighbor O(1))
  - only function of relative quantities (relative positions among robot and between robots/obstacle)
  - passifying action using the Tank machinery

Connectivity Maintenance

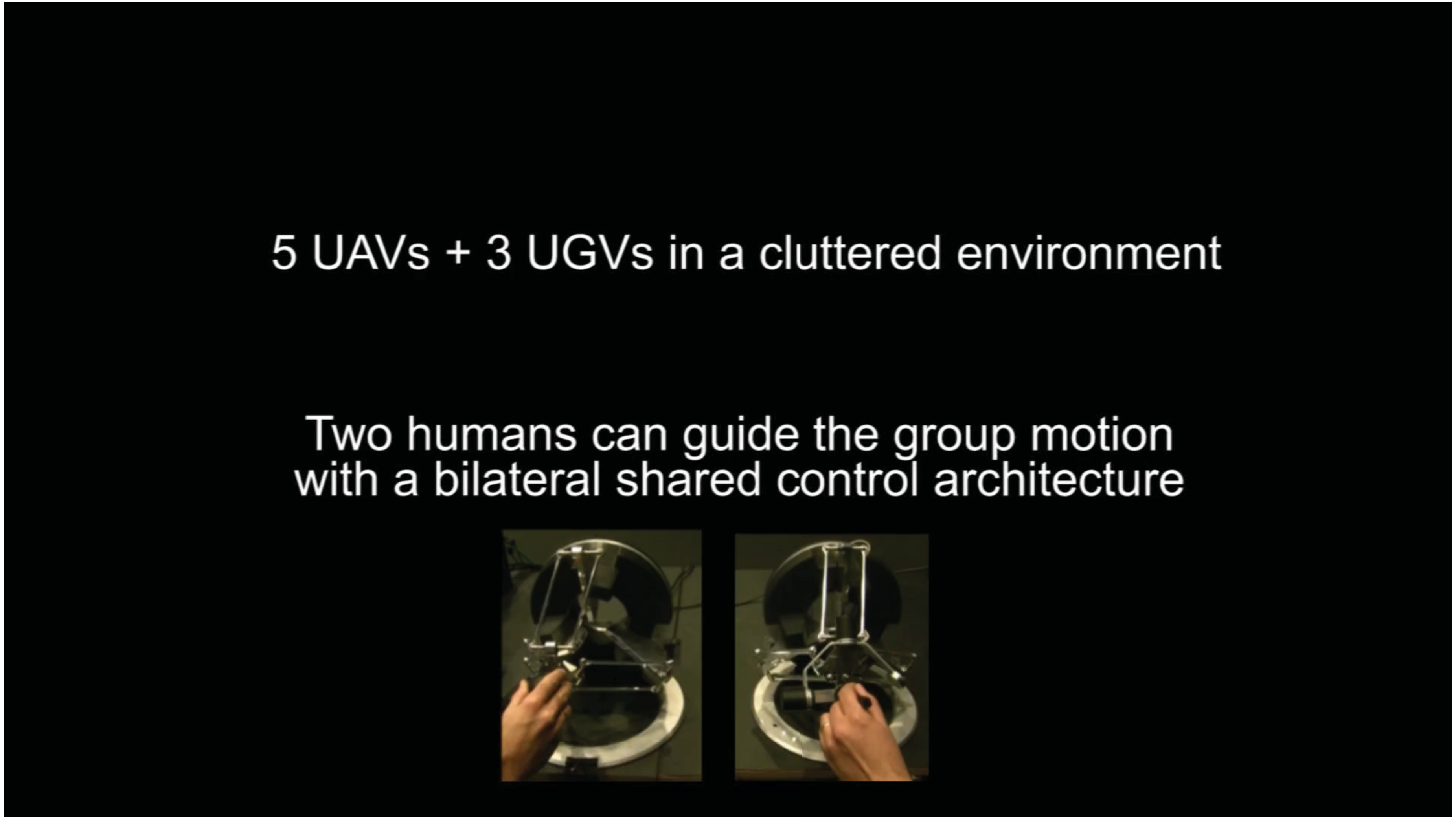
- Simulations with $N = 8$ robots (5 quadrotor UAVs and 3 ground robots)
- Experiments with $N = 4$ quadrotor UAVs

RSS 2011, IJRR (submitted)

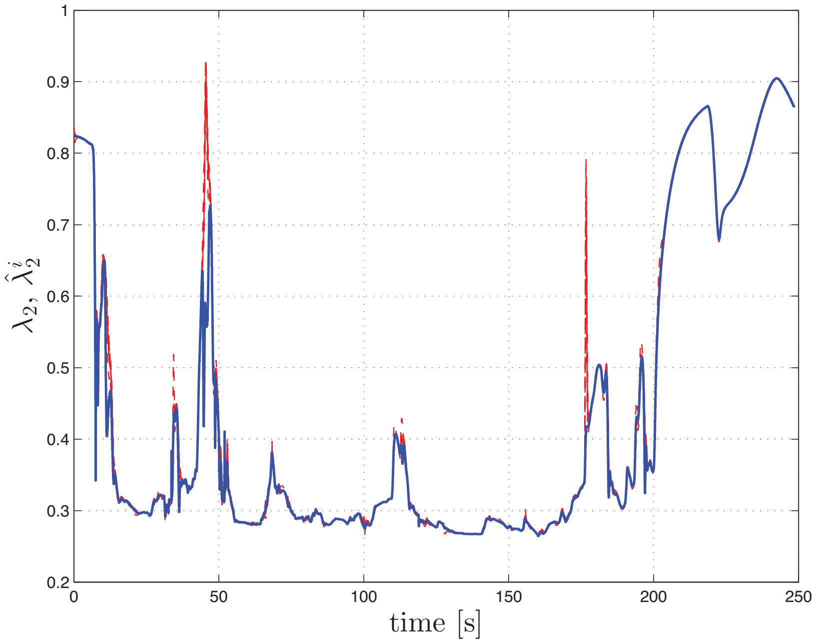


Connectivity Maintenance

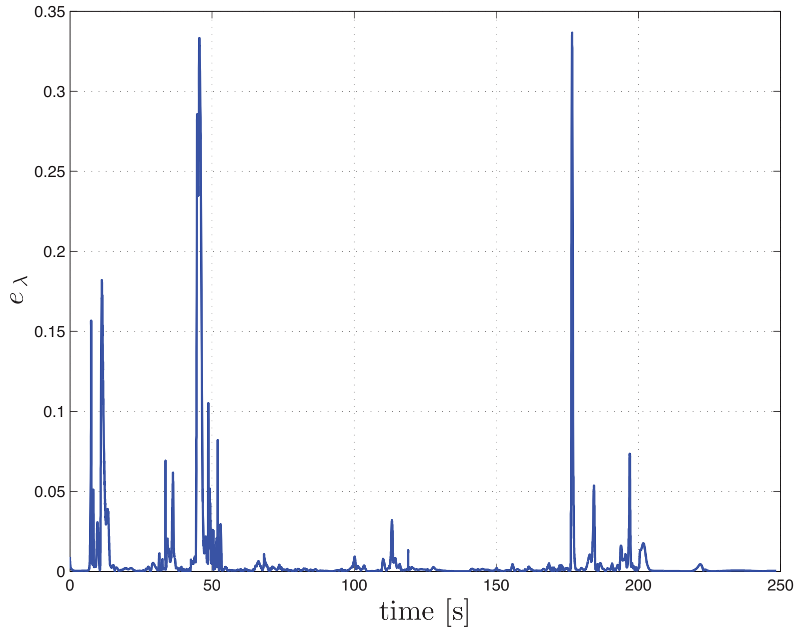
- Simulations with $N = 8$ robots (quadrotor UAVs and ground robots) RSS 2011, IJRR (submitted)



Connectivity Maintenance



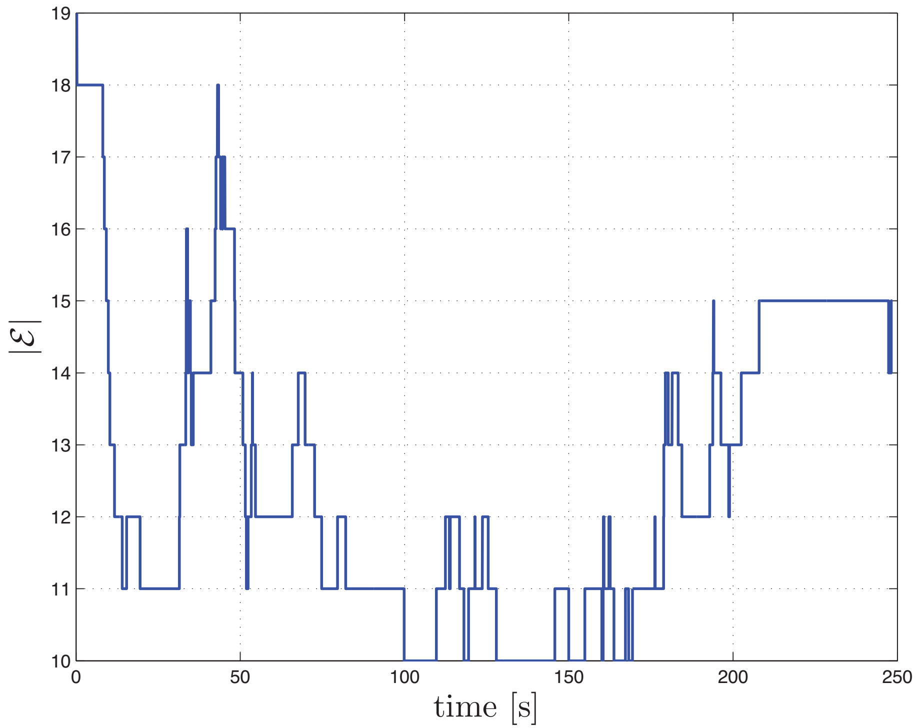
Real λ_2 (solid) vs. estimated $\hat{\lambda}_2^i$ (dashed)



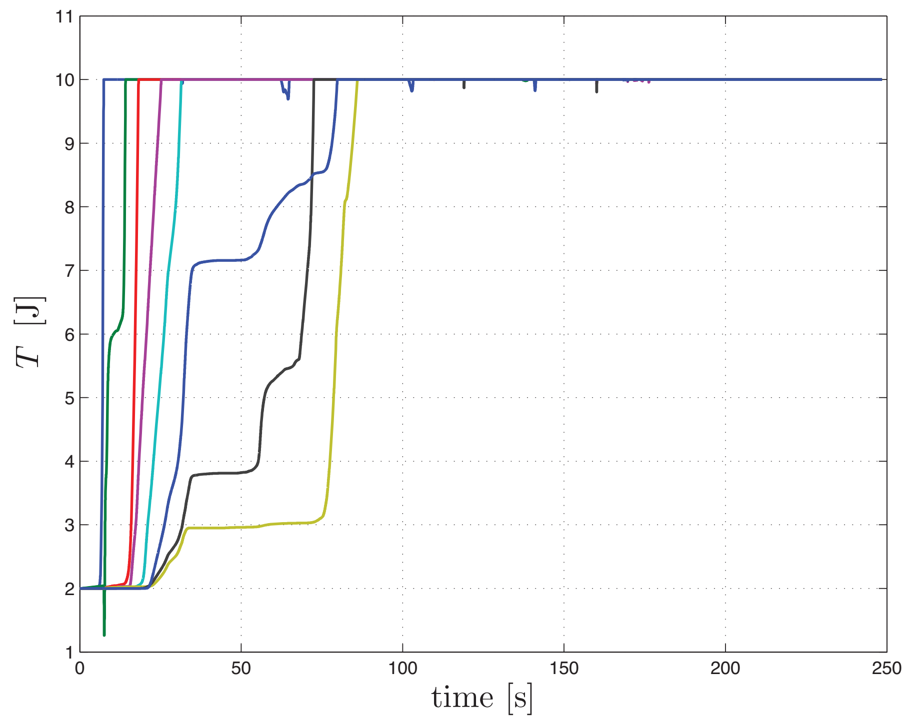
Average estimation error

$$e_\lambda(t) = \frac{\sum_{i=1}^{N} |\lambda_2(t) - \hat{\lambda}_2^i(t)|}{N}$$

Connectivity Maintenance



Number of edges in $\mathcal{G}$

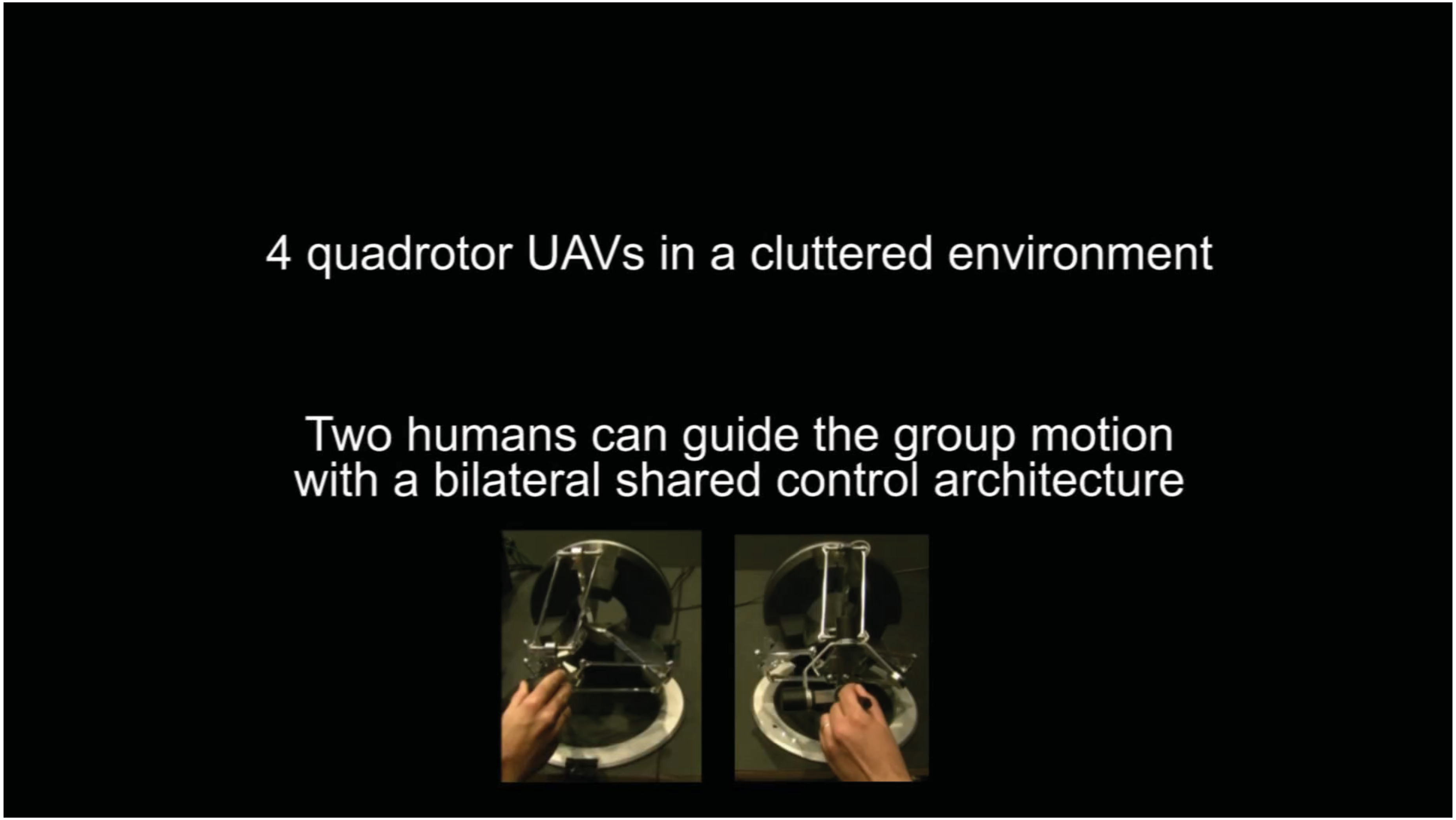


Tank energies $T(x_t)$

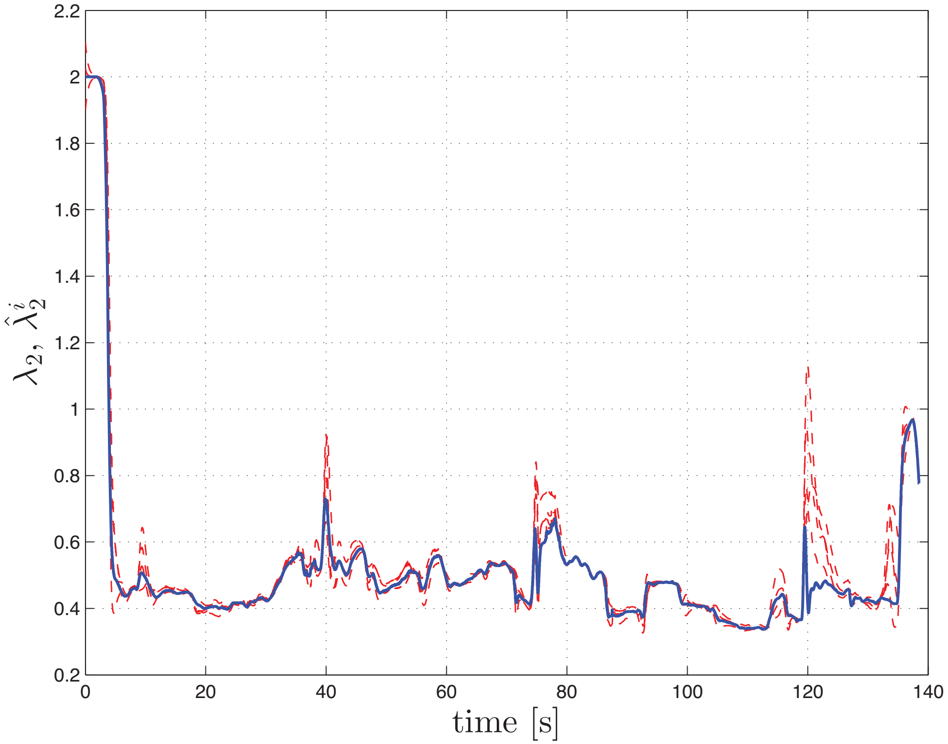
Connectivity Maintenance

- Experiments with $N = 4$ quadrotor UAVs

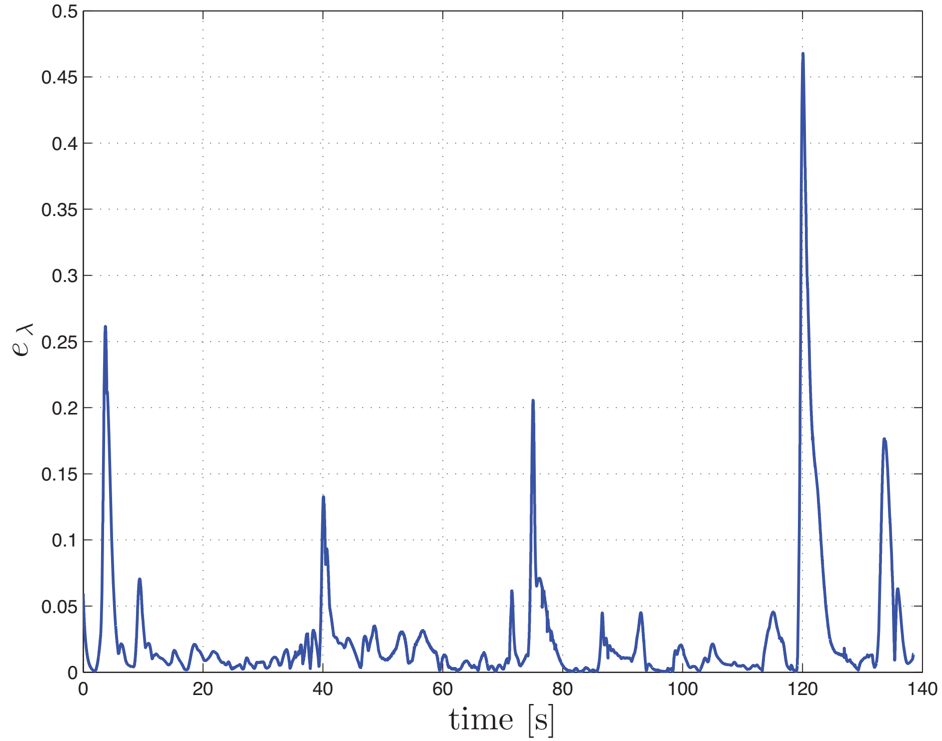
RSS 2011, IJRR (submitted)



Connectivity Maintenance



Real λ_2 (solid) vs. estimated $\hat{\lambda}_2^i$ (dashed)



Average estimation error

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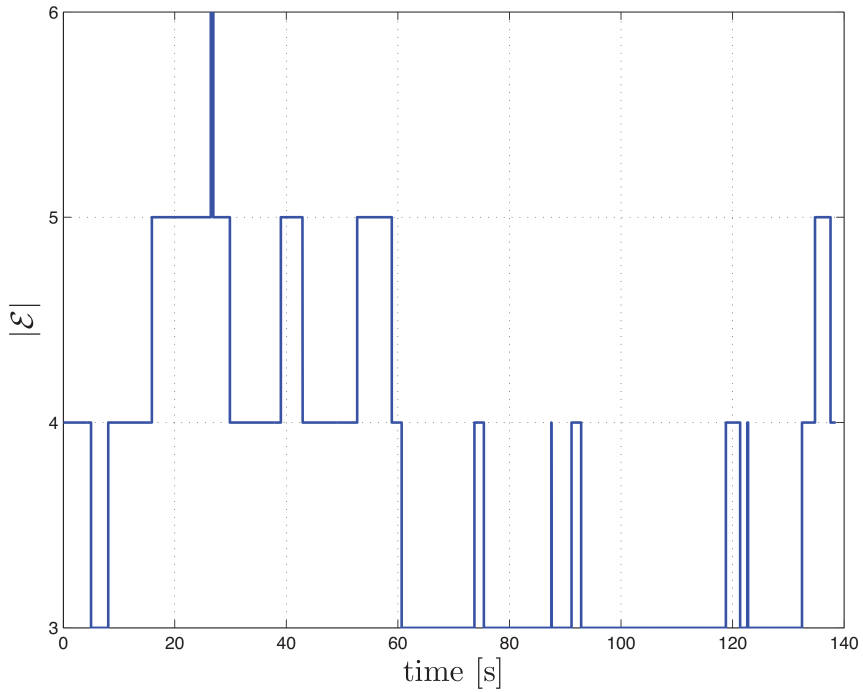
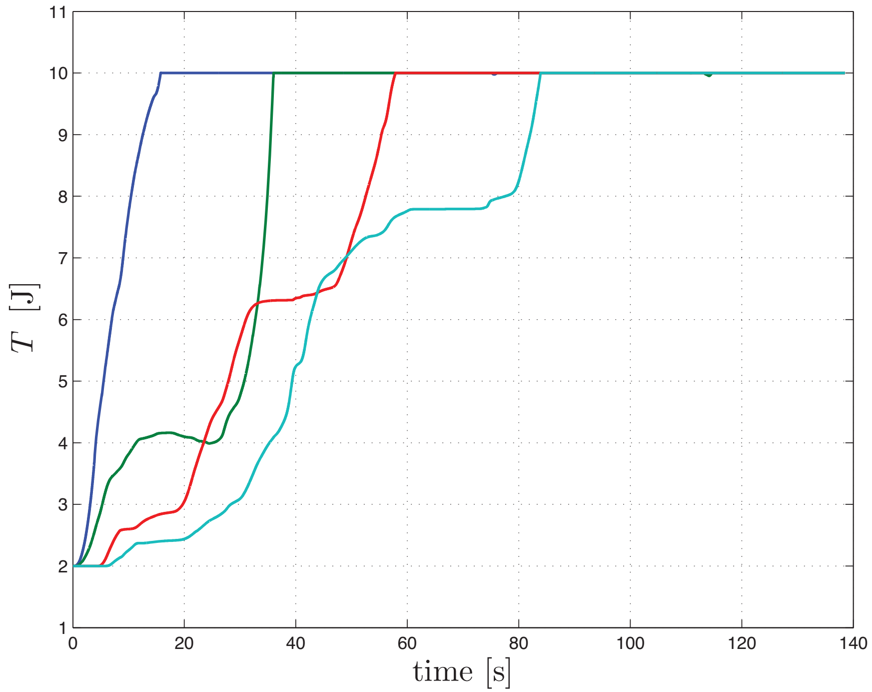
Connectivity Maintenance



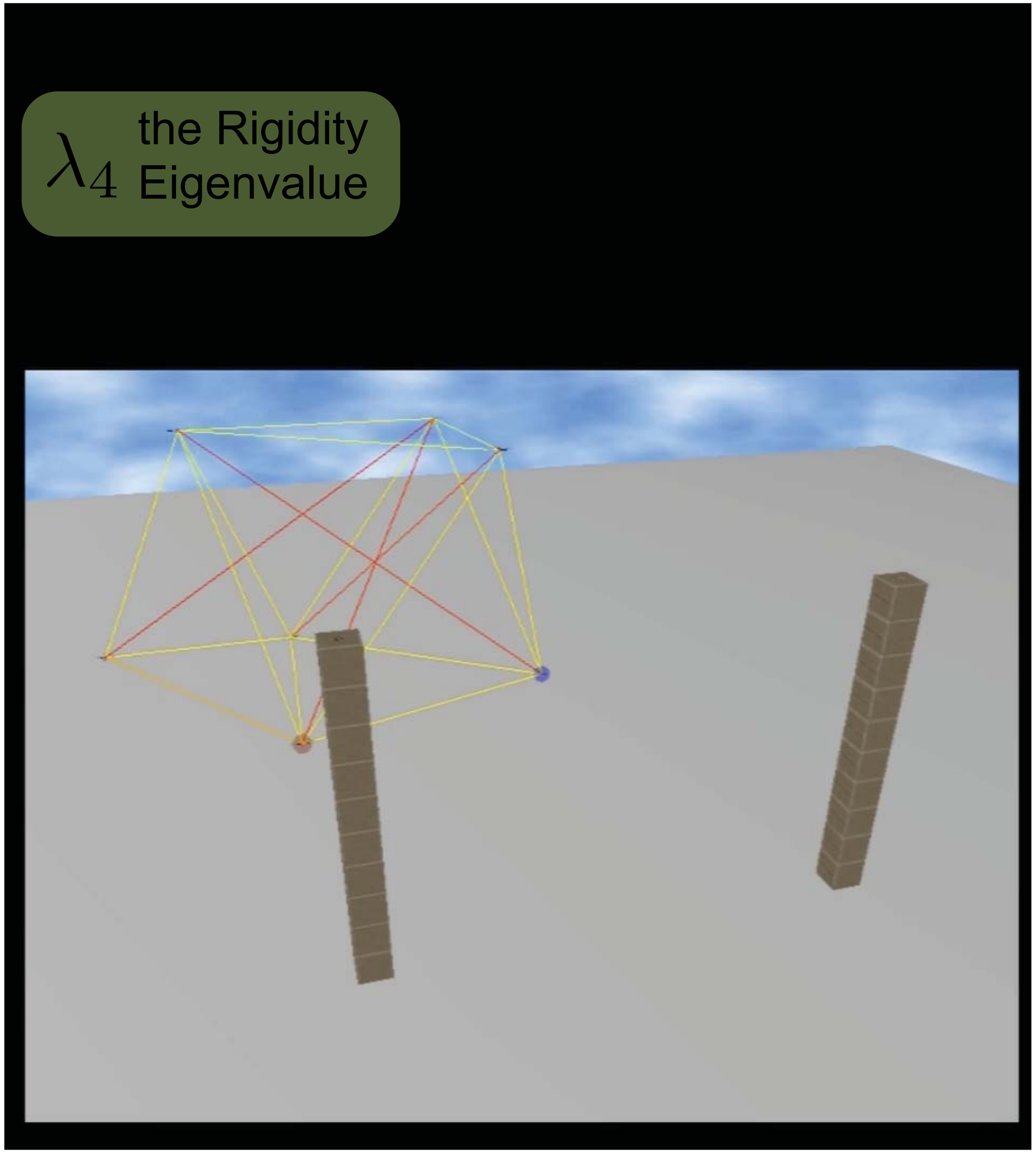
Number of edges in $\mathcal{G}$



Tank energies $T(x_t)$

Rigidity Maintenance

- An extension (RSS 2012)
- one can also define a "Rigidity Eigenvalue" λ_4 and apply the same machinery
- rigidity maintenance with the same constraints and requirements as before
- Still flexibility in the graph topology
- Freedom in gaining/losing links as long as $\lambda_4 > 0$

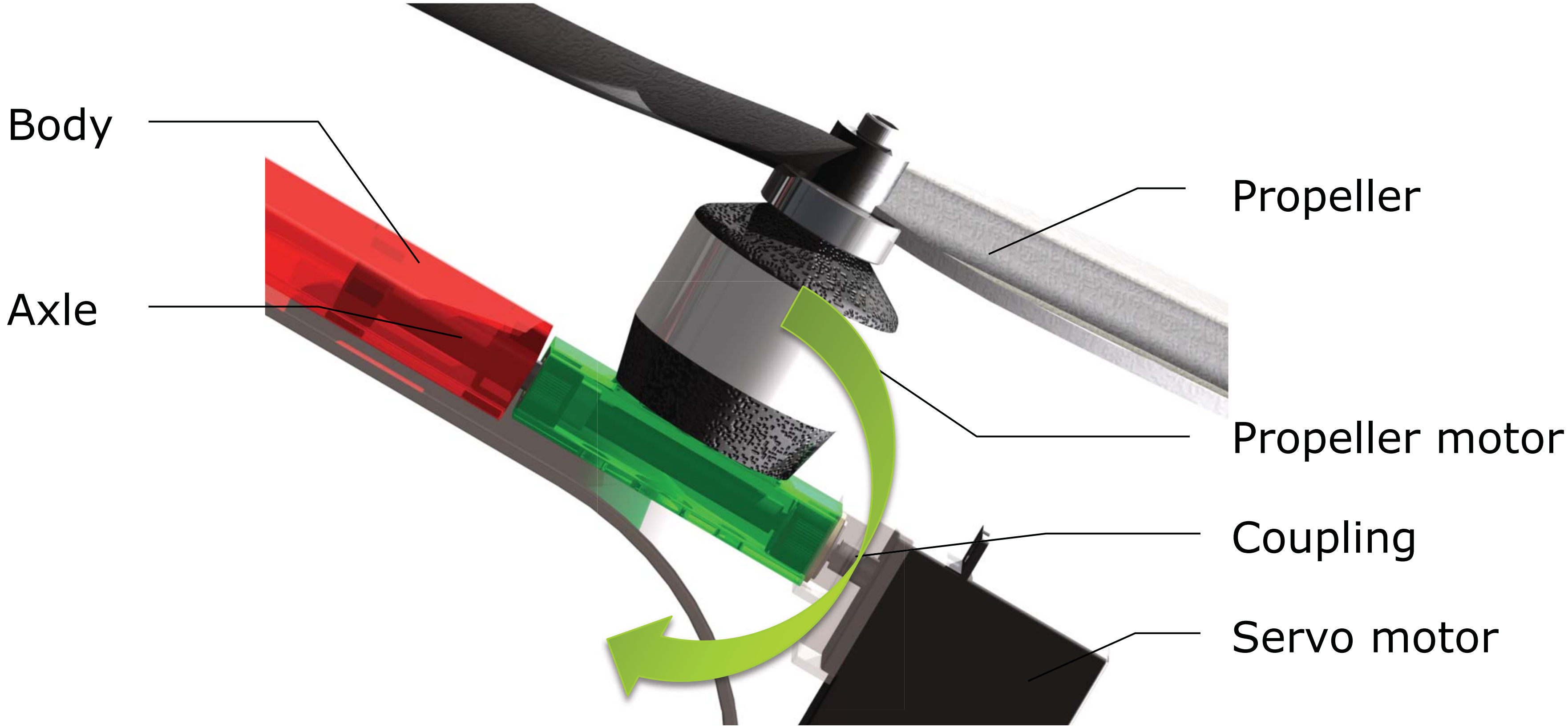


Additional Related Activities

- Consider different actuation strategies for flying robots to improve their maneuverability for inspection or interaction with the environment
  - Quadrotor with (actuated) tilting propellers

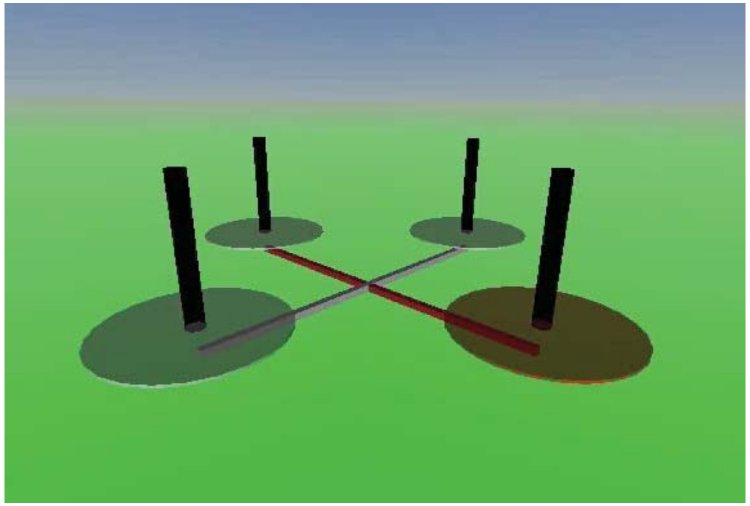
ICRA 2012

Additional Related Activities

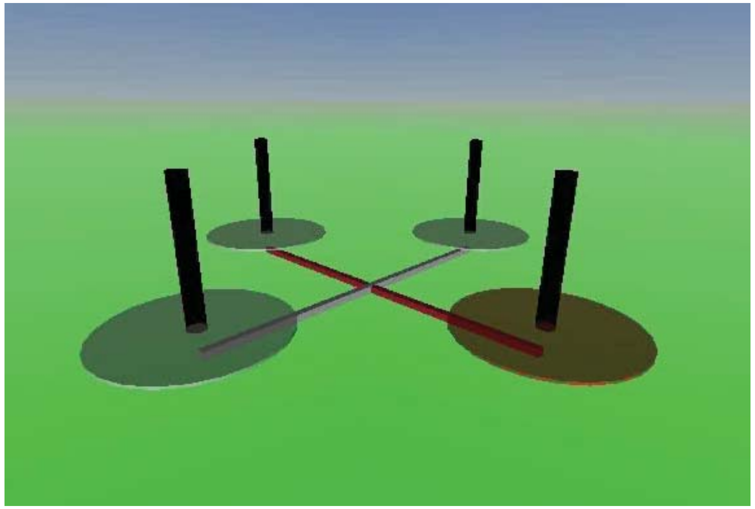


Additional Related Activities

- Some “new” maneuvers



ICRA 2012

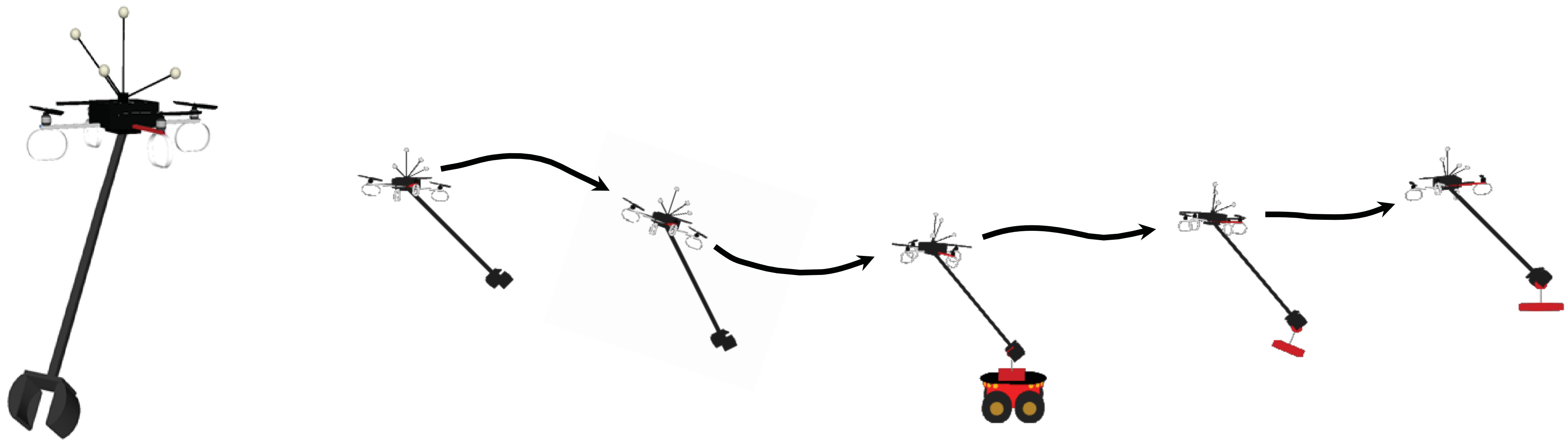


Rotation on the spot while **minimizing** energy consumption

Rotation on the spot **without minimizing** energy consumption

Additional Related Activities

- Equip Quadrotors with Grippers for manipulation "on-the-fly"



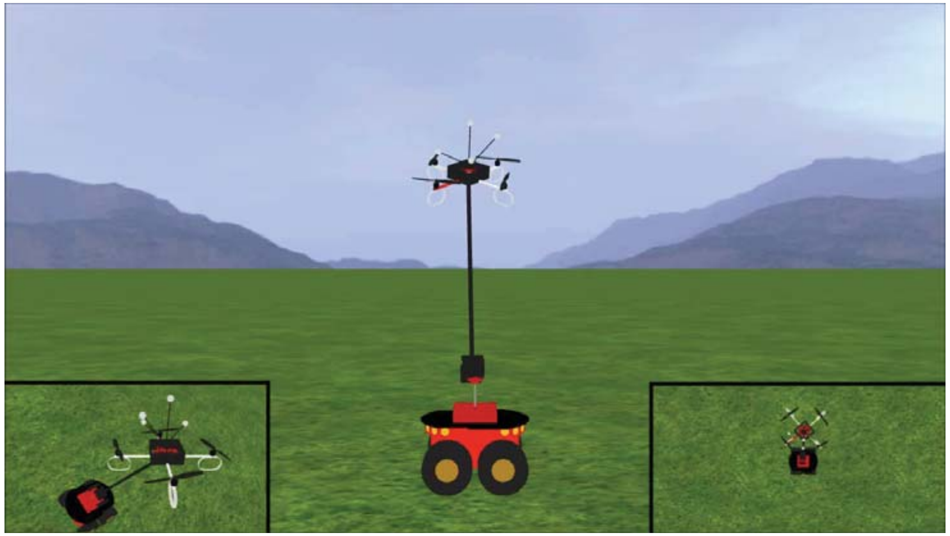
- Time-optimal planning with actuator constraints and full quadrotor dynamics
- Exploitation of the quadrotor output flatness for trajectory planning

IROS 2012

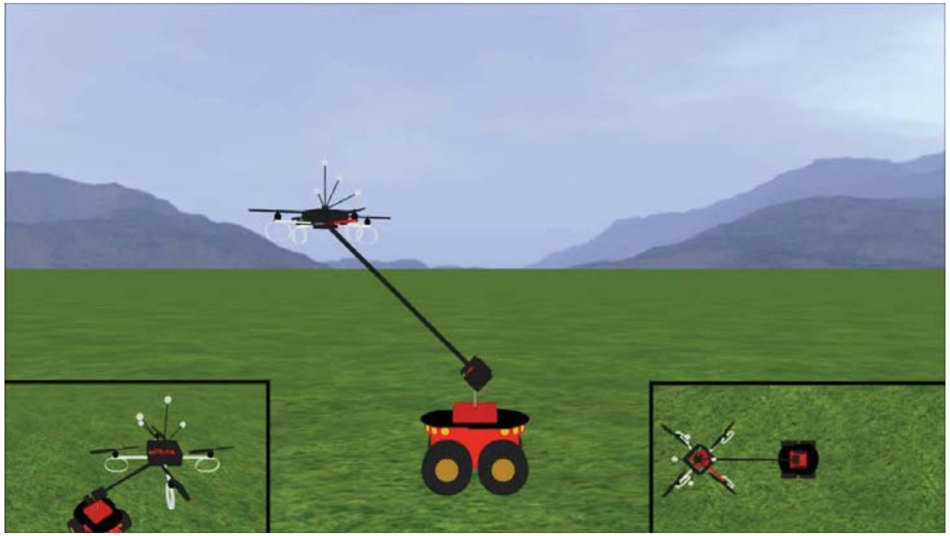
Additional Related Activities

- Equip Quadrotors with Grippers for manipulation “on-the-fly”

IROS 2012



Gripping trajectories Class I

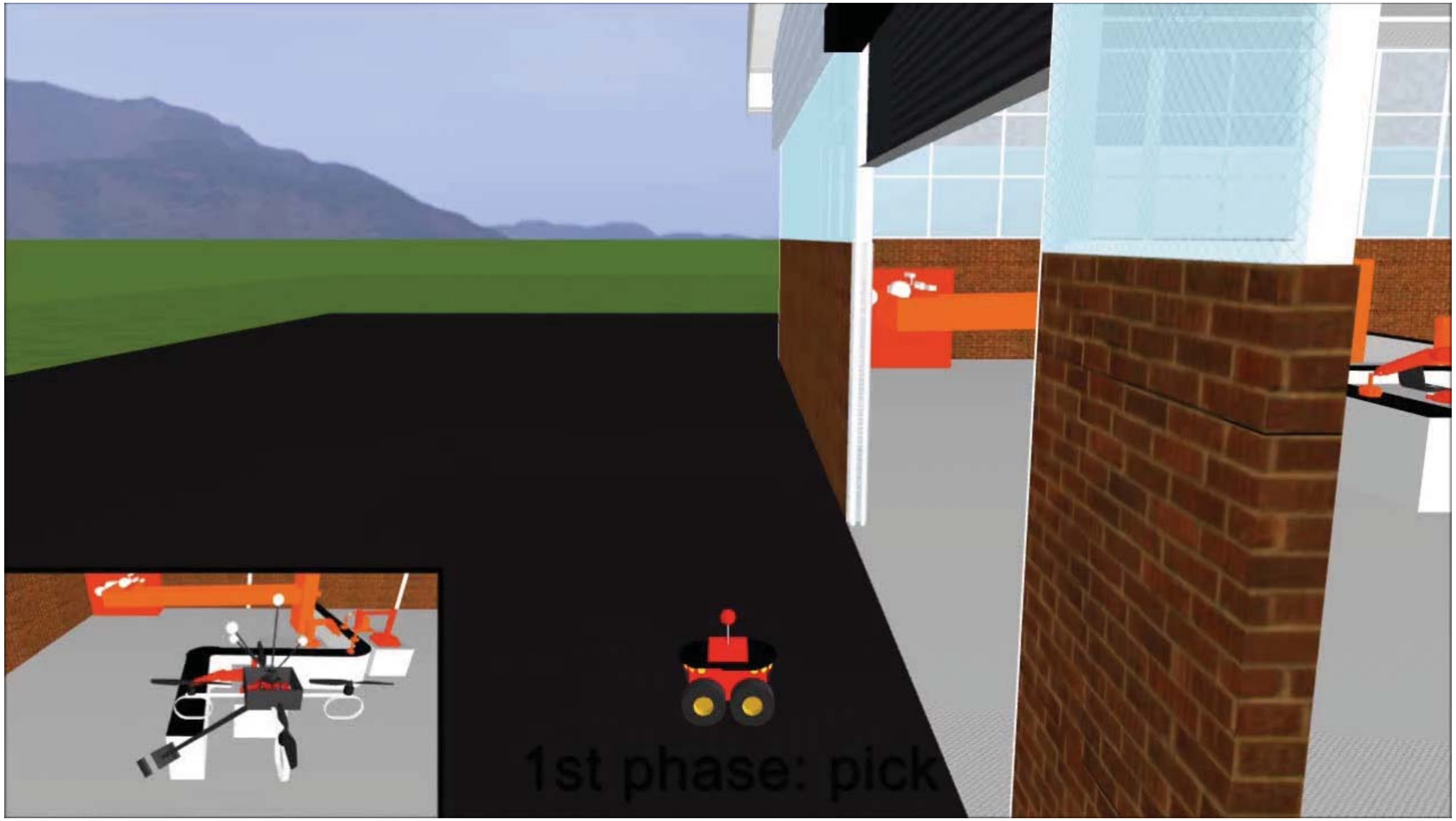


Gripping trajectories Class II

Gripping while in hover is “spanned” by these two classes

Additional Related Activities

- Equip Quadrotors with Grippers for manipulation “on-the-fly”



- A complete sequence of pick and place operations

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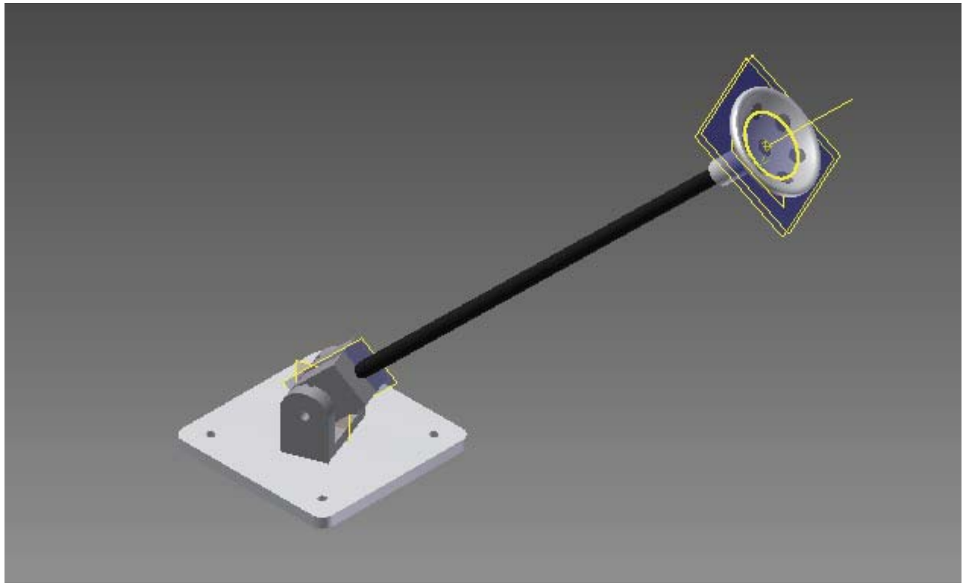
Ongoing activities at the MPI

- Equip Quadrotors with Grippers for manipulation “on-the-fly”
- implementation on a real quadrotor UAV



Ongoing activities at the MPI

- Interactive Planning of Persistent Trajectories for Human-Assisted Navigation of Mobile Robots

- Cyclic motion executed by a mobile robot
- The human operator teleoperates suitable parameters of the curve
- The curve autonomously deforms in presence of obstacles
- "Integral" haptic feedback on the global deformation

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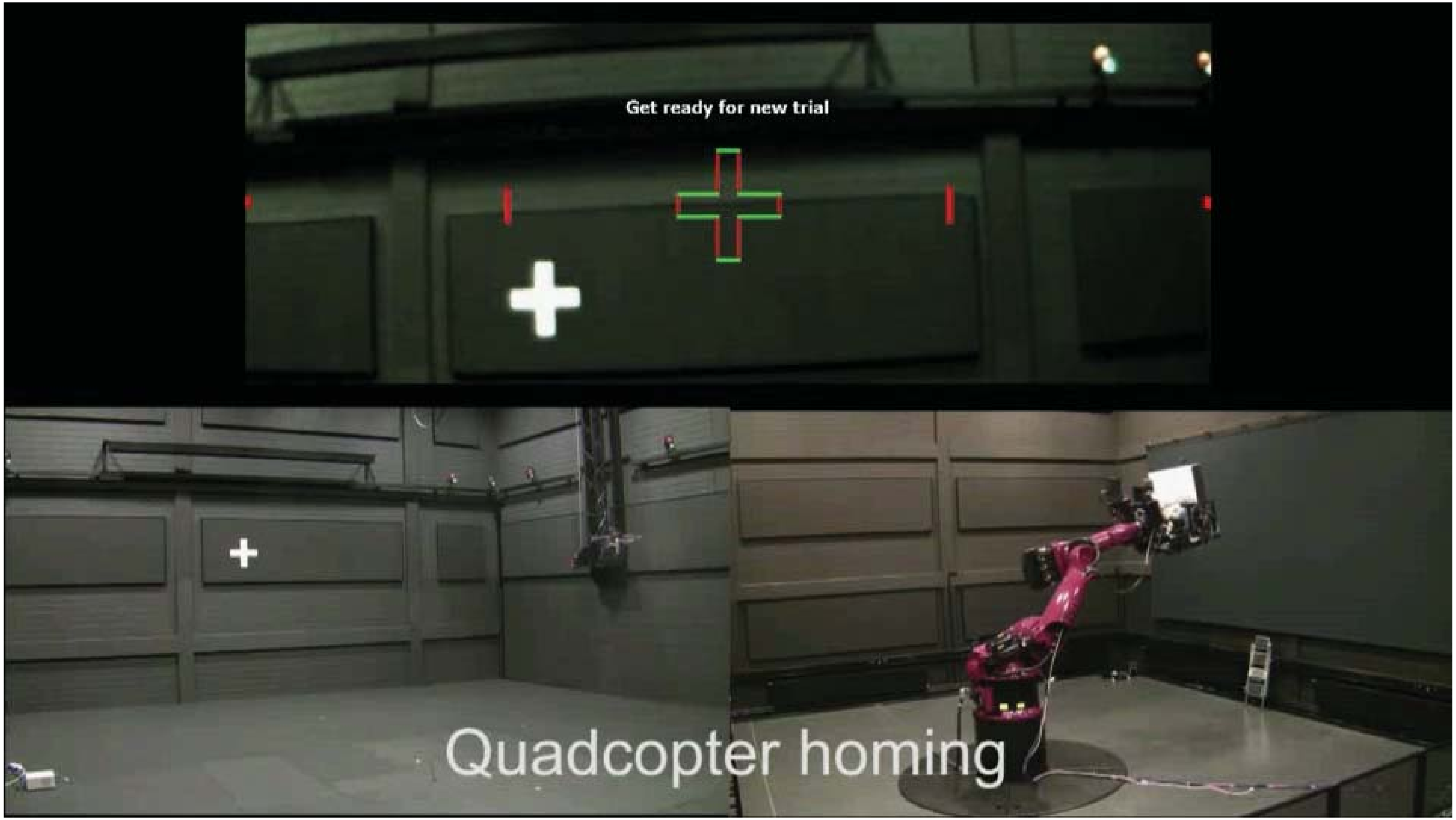
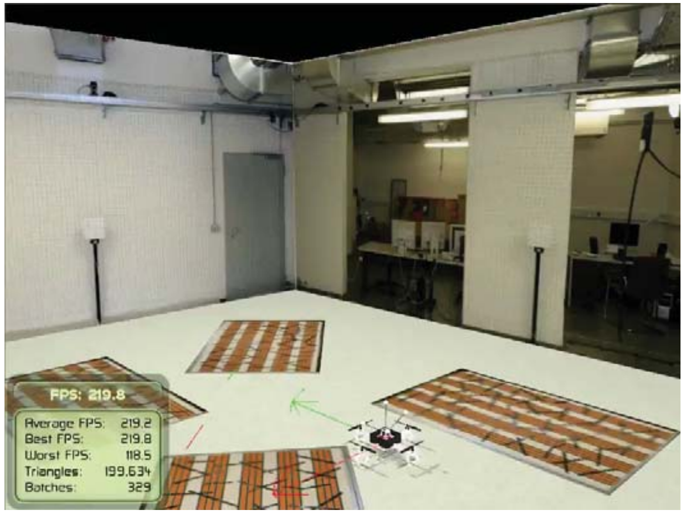
Other Perspectives

- Exploit different ways to provide feedback to human subjects

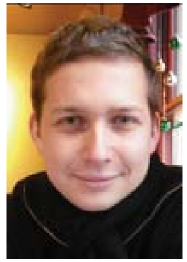


Acknowledgments

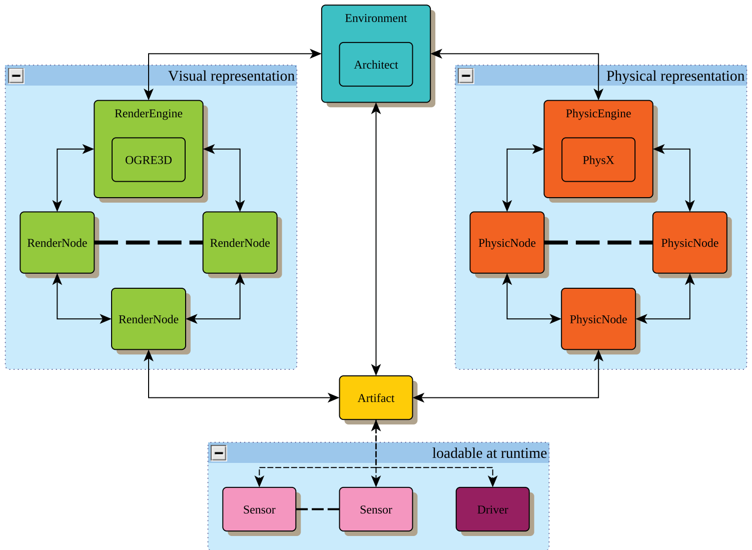
- The simulation environment and middleware software for running simulations and experiments was co-designed with

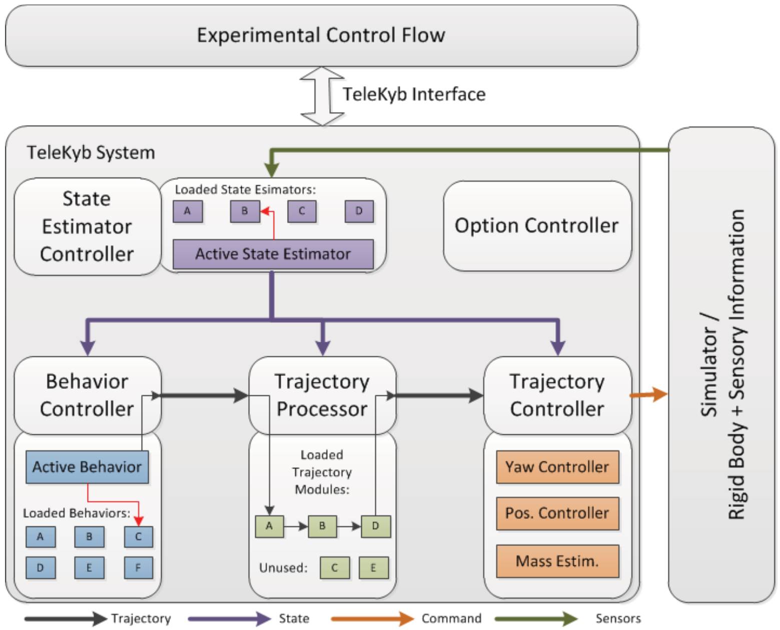


Johannes Lächele
MPI for Biological Cybernetics



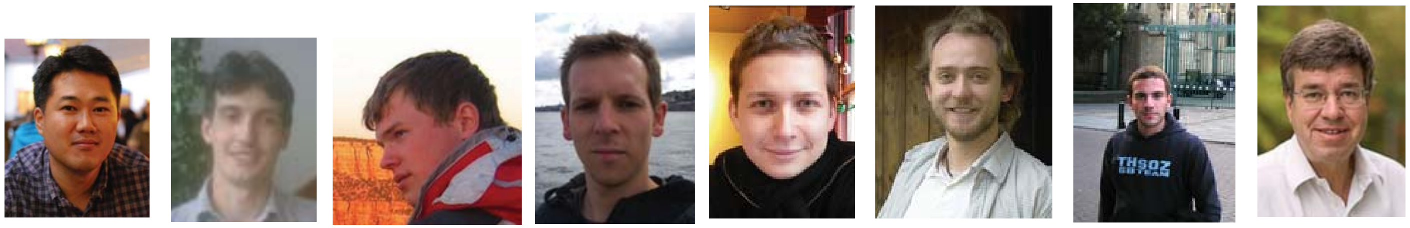
Martin Riedel
MPI for Biological Cybernetics





Acknowledgments

thanks to my collaborators



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Thanks to the audience!
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