Collective Control, State Estimation and Human Interaction for Quadrotors in Unstructured Environments

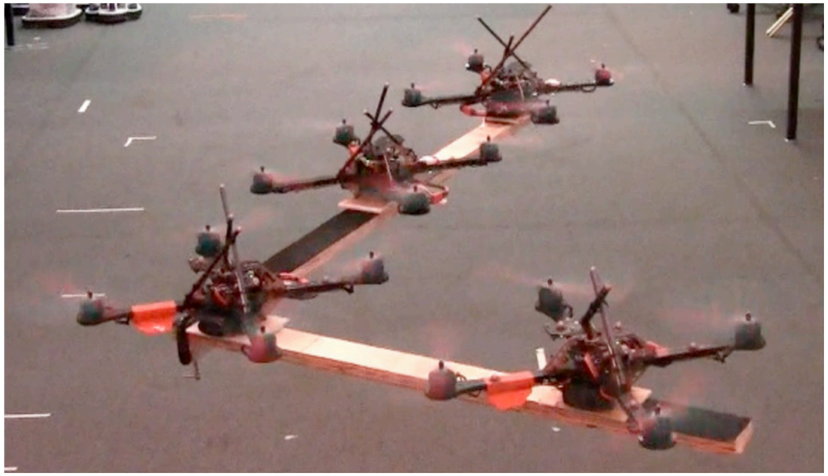
Dr. Paolo Robuffo Giordano

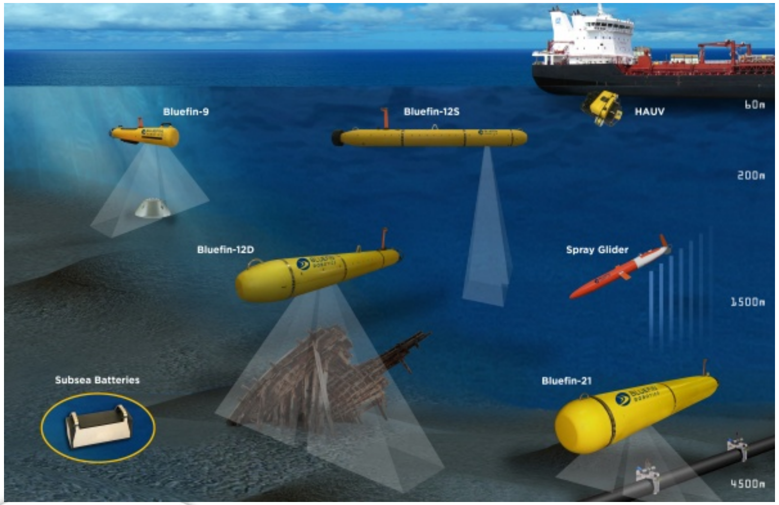
Lagadic group

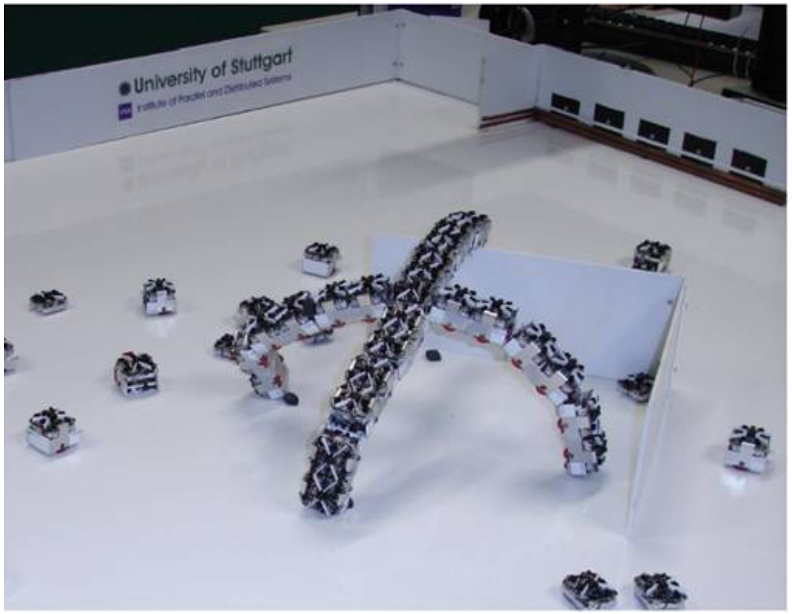
Inria Rennes Bretagne Atlantique & Irisa

http://www.irisa.fr/lagadic

(Multi-)Mobile Robotics







Flying Robots

DHL

amazon

Flying Robots

© Aerial Robotics Cooperative Assembly System (ARCAS)
FP7-ICT-2
FP7 project nº: 287617

© Aerial Robotics Cooperative Assembly System (ARCAS)
FP7-ICT-2
FP7 project nº: 287617

EU FP7 Project Arcas: 6 M€

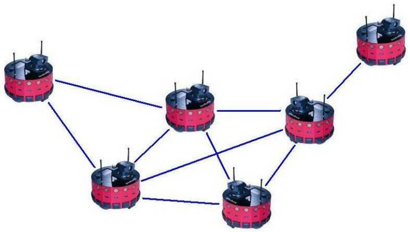
ARTVA HANGING FROM QUADROTOR TO AVOID ELECTROMAGNETIC DISTURBANCES

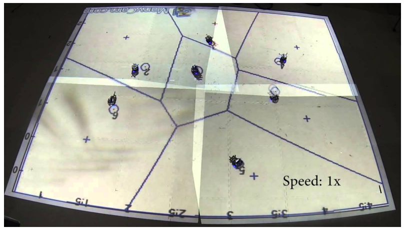
SHERPA

EU FP7 Project Sherpa: 11 M€

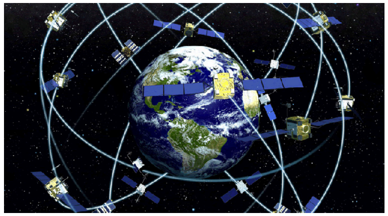
Multi-Robot Systems

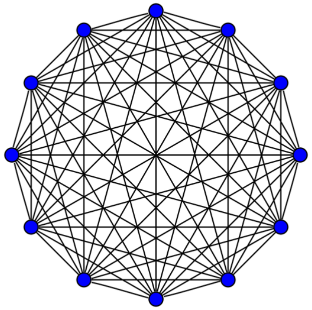
- Example of typical missions:
  - reach/maintain a desired spatial arrangement (formation control)
  - follow a reference motion (e.g., a leader)
  - collectively reach a common point (rendez-vous)
  - obtain optimal coverage of an area
  - …

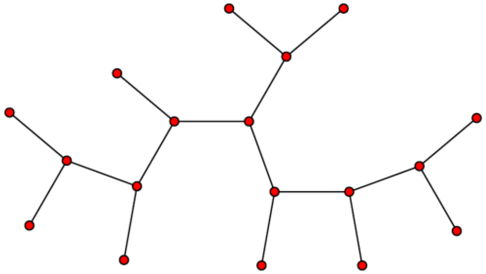




- Available technology
  - sensing (onboard/offboard)
  - communication (all-to-all, 1-hop, multi-hop)
  - processing units (onboard/offboard)



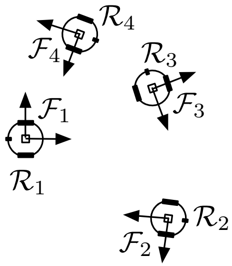


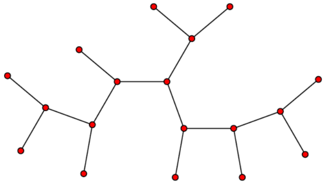


Multi-Robot Systems

- Ideal scenario:
  - availability of relative poses w.r.t. any other robot in the group in a common inertial frame
  - possibility to communicate with any other robot in the group with no delays
  - unlimited memory and processing power (onboard/offboard)
  - ....

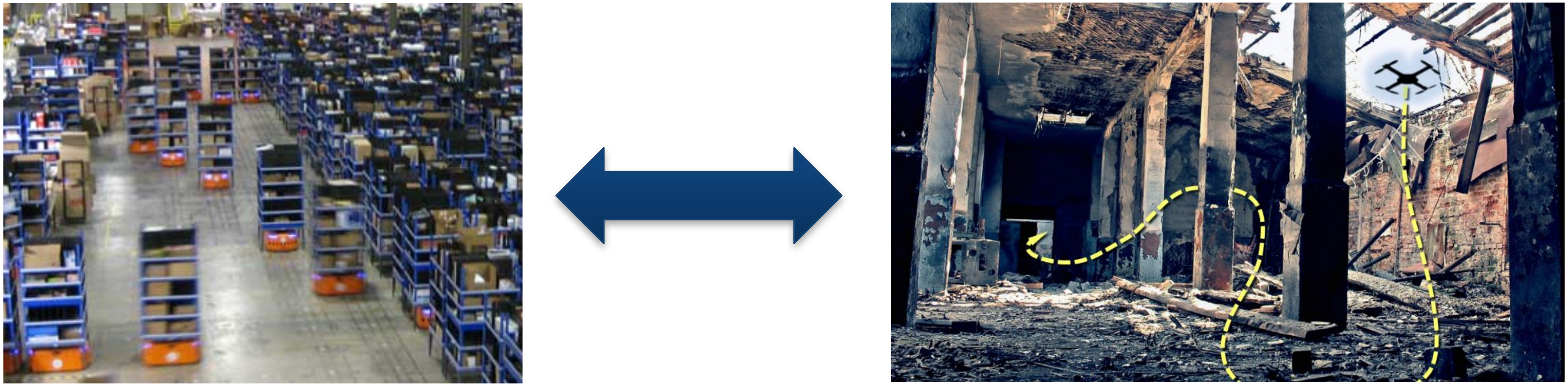
- However, this is seldom the case: in many (realistic) applications several limitations/requirements/constraints
  - Limited sensing: partial measurement of the other robot states (e.g., distance, bearing)
  - Limited sensing: lack of a common shared frame
  - Limited sensing: occlusions, field of view, maximum range
  - Limited communication: occlusions, maximum range, delays
  - Limited communication: maximum data rate
  - Limited memory and processing power





(Multi-)Flying Robots

- Many possible real-world applications (and big interest from non-academic public)
- However, **still many challenges to be solved**, especially in unstructured environments



- Just to cite a few:
  - Reliable flight control in harsh conditions
  - Robust state estimation from (mainly) onboard sensing (e.g., vision)

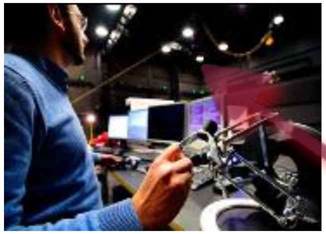
  → Local autonomy

  - Mission control: where to go and what to do ?
  - Task/resource allocation, decision making, etc.

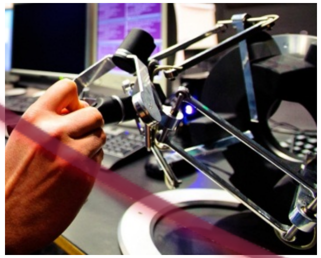
  → Human assistance

Shared Control of Multiple Aerial Robots

Human Operator



Haptic Interface



Communication Channel

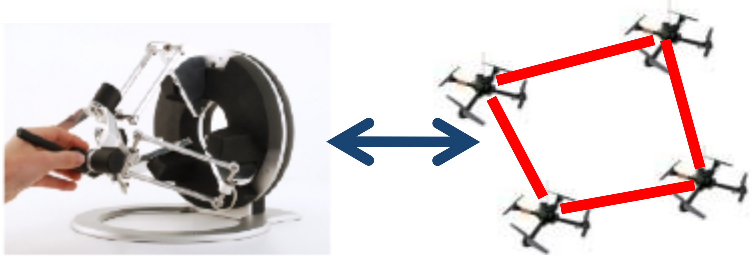
Multi-UAV System

Remote Environment

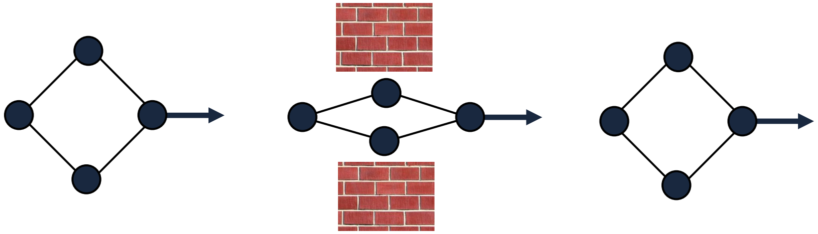
- Human operator gives **high-level motion commands** and receives a suitable **force feedback**

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

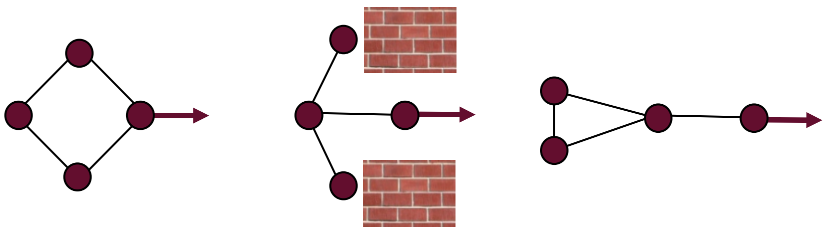
Two Possible Approaches

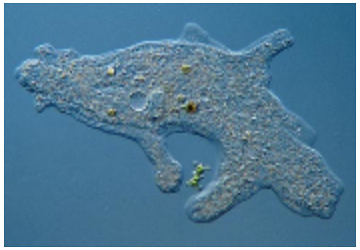


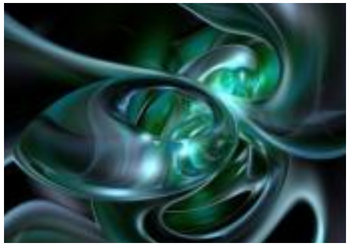
Constant Topology



Unconstrained Topology

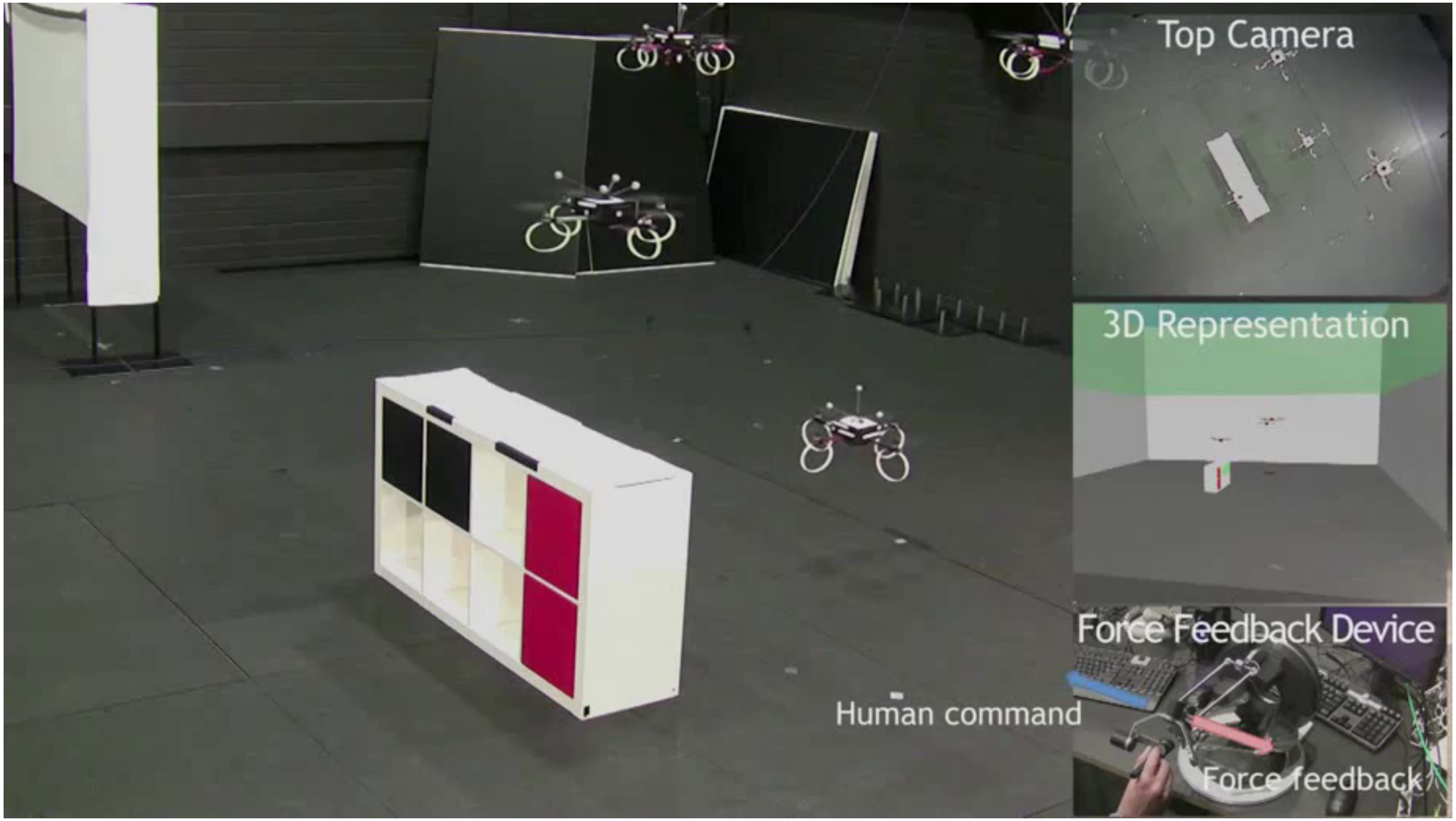






- General “**tele-navigation**” framework
- Basis for building any **higher-level exploration** or **generic cooperative task**
- In general, **force feedback** = mismatch between **commanded “motion task”** and **its actual realization**

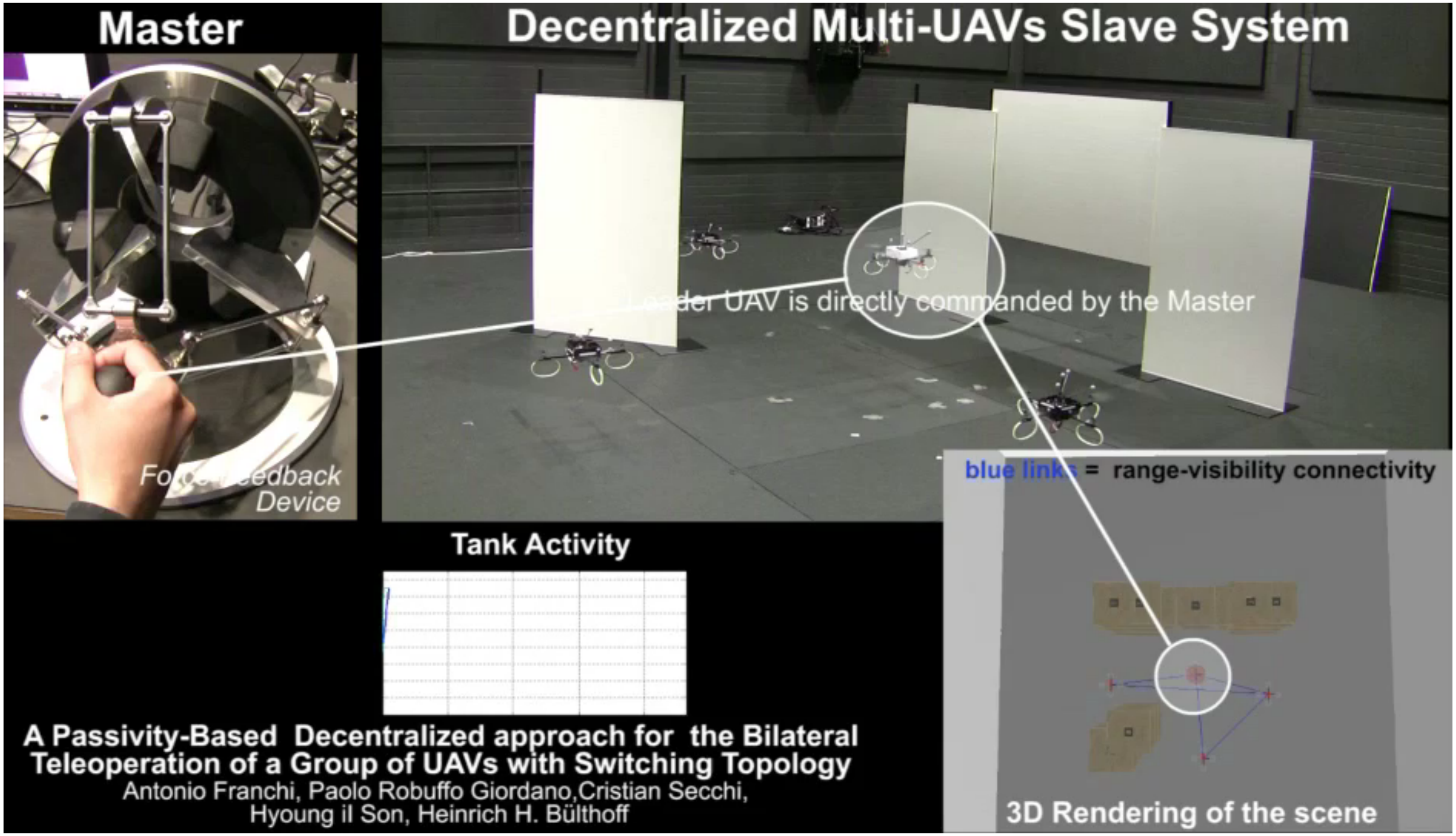
Constant Topology using Distances

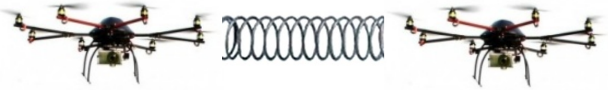


- The human operator commands the collective motion (a common velocity vector)
- Obstacle avoidance is taken into account
- The instantaneous mismatch between command and executed motion becomes a force cue
- Requires knowledge of relative positions in a common shared frame

ICRA 2011, T-MECH 2013

Unconstrained Topology using Distances





- Range and visibility determine presence of inter-robot “interaction” (spring-like couplings)
- Force-feedback = instantaneous mismatch between commanded and actual leader velocity
- Requires knowledge of relative positions in a common shared frame

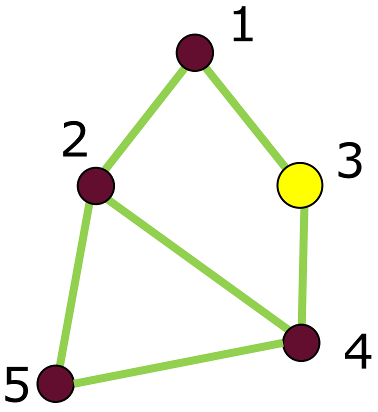
ICRA 2011, IROS 2011
ICRA 2012, TRO 2012

Maintenance of Global Properties

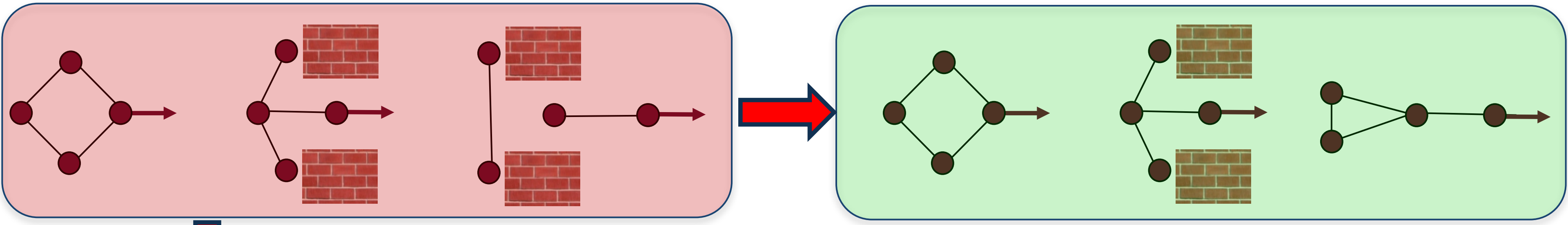
- Previous works exploit several assumptions, e.g.,
  - availability of the full relative position among neighboring pairs (despite controlling distances)
  - possibility to continuously share information during the task

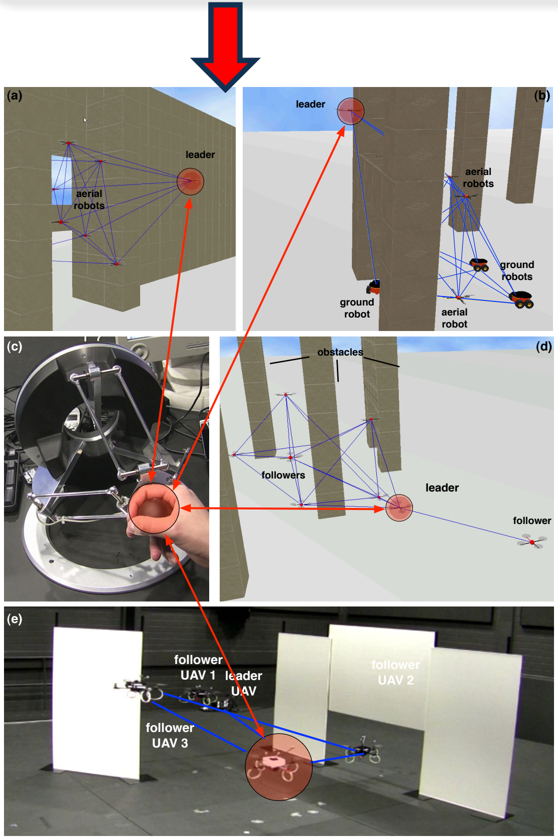
- Two main global/architectural properties of the underlying (sensing/communication) graph are of help for an actual decentralized implementation
  - **Graph connectivity**
  - **Graph rigidity**

- **Limited sensing/communication** and **limited computing power/memory** -> need of decentralized (scalable) control/estimation algorithms
  - **Avoid** measurement of the state of the whole group
  - Keep a $O(1)$ complexity per neighbor
  - Need to preserve **group connectivity** for allowing propagation of information



Connectivity Maintenance





- Group connectivity is a necessary condition for allowing a group or robots achieving a common task by resorting to only local information

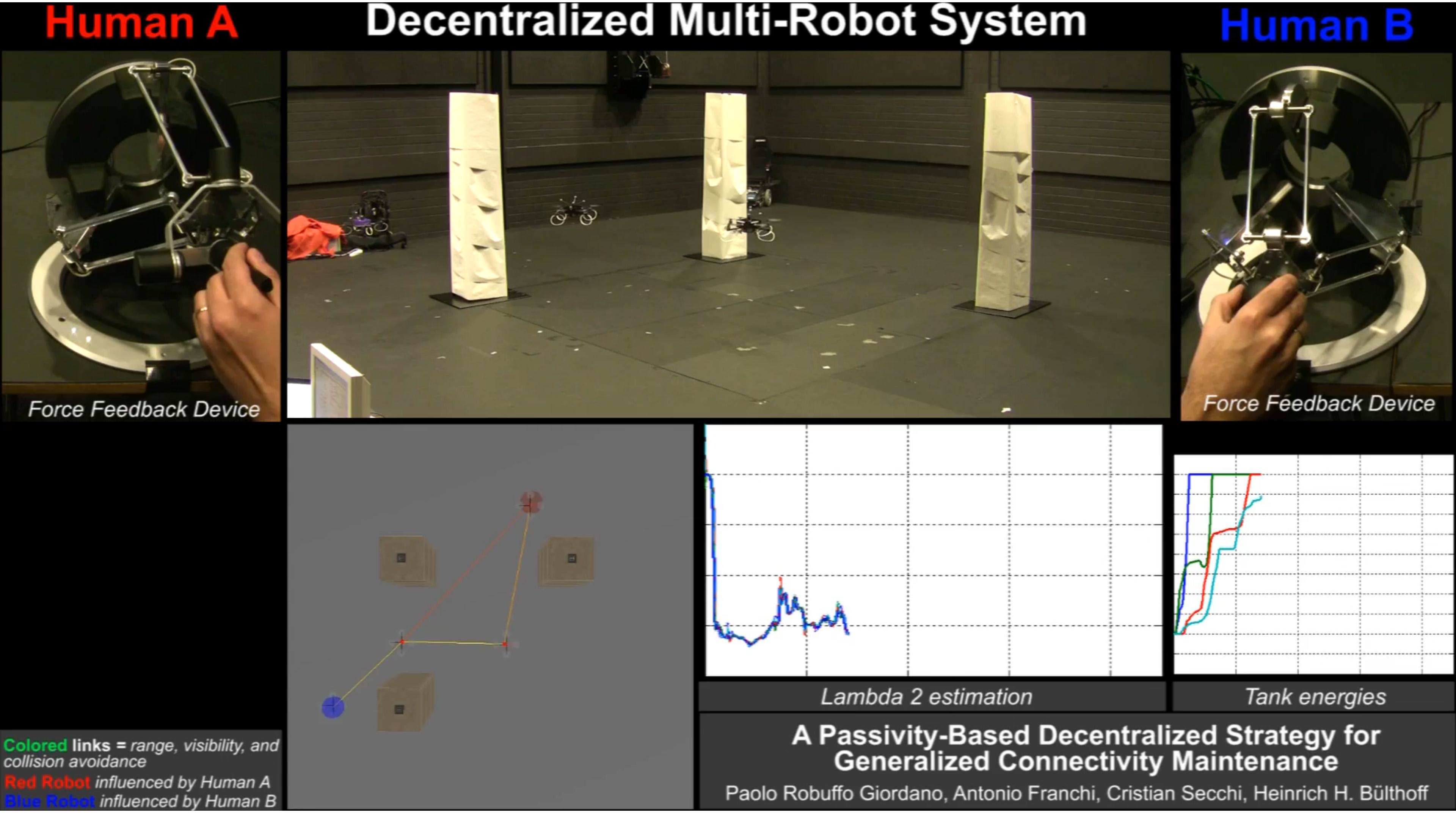
- Extension able to enforce connectivity maintenance while still allowing **(almost) arbitrary splits** and **joins**
  - **Especially relevant when the graph topology is dictated by sensing constraints**

- Based on (decentralized) “gradient control” of the connectivity eigenvalue λ_2 (second smallest eigenvalue of the graph Laplacian L)

$$u_i \approx \frac{\partial \lambda_2}{\partial x_i}$$

RSS 2011, ICRA 2013, IJRR 2013

Connectivity Maintenance



Human A

Decentralized Multi-Robot System

Human B

Force Feedback Device

Force Feedback Device

Colored **links** = *range, visibility, and collision avoidance*

Red Robot *influenced by Human A*

Blue Robot *influenced by Human B*

Lambda 2 estimation

Tank energies

A Passivity-Based Decentralized Strategy for Generalized Connectivity Maintenance

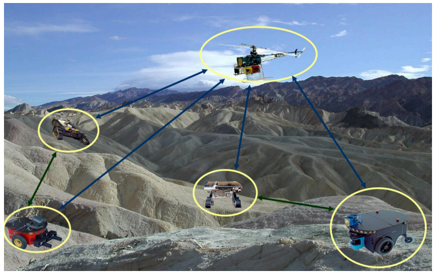
Paolo Robuffo Giordano, Antonio Franchi, Cristian Secchi, Heinrich H. Bülthoff

<u>**RSS 2011, ICRA 2013, IJRR 2013**</u>

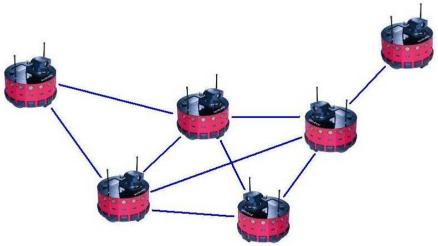
Formation Control and Localization

- Assume the robot group can measure some function of their relative pose with onboard sensing (e.g., relative distance, relative bearings)

- **Relative localization**
  - Available measurements -> reconstruction of the current robot relative poses in a common shared frame

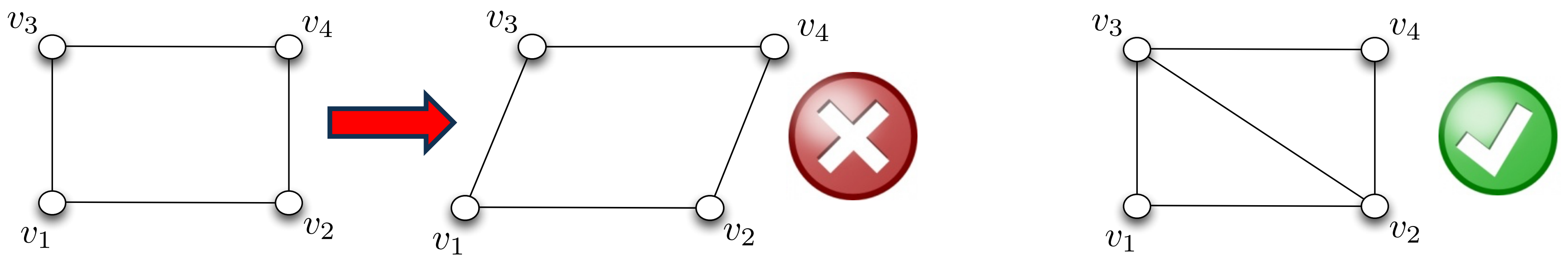


- **Formation control**
  - Regulation of the available measurements -> reaching the desired robot poses in a common shared frame

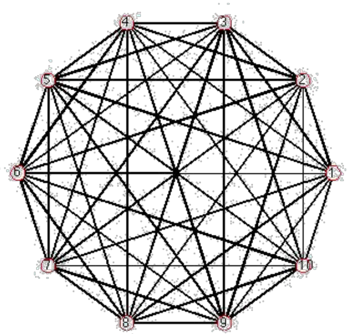


- Need to preserve **formation rigidity** (~ allow for cooperative localization common reference frame from onboard relative and partial sensing)

Rigidity



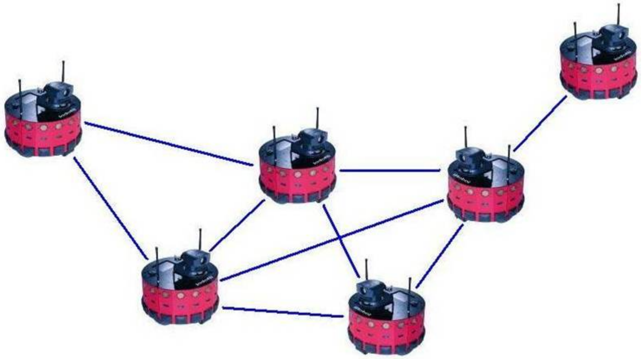
- A “framework” (graph + agent poses) is rigid if it cannot be deformed “**while preserving the pair-wise geometrical constraints**”



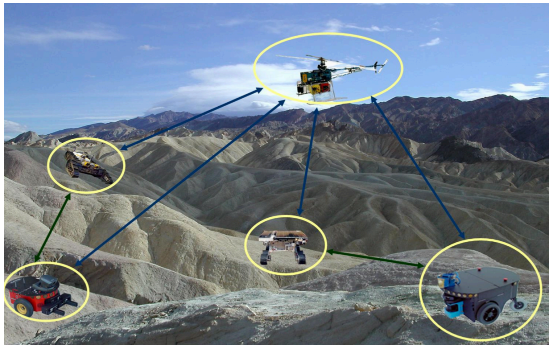
- Complete graph: need to measure/control/enforce $\boxed{N(N-1)/2}$ constraints (the complexity is $O(N^2)$)
- However, framework rigidity is often possible with only a $\boxed{O(N)}$ set of constraints
- Distance constraints on the plane

	$N(N-1)/2$	$2N-3$
$N=3$	3	3
$N=4$	6	5
$N=10$	45	17

Rigidity: what for ?

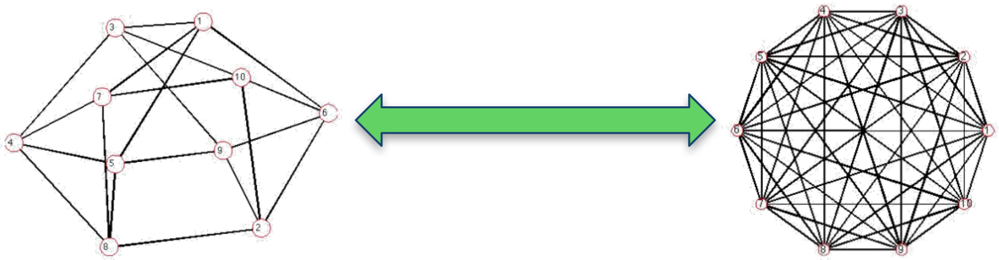


- **Formation control**
  - Regulation of inter-robot constraints =
    the desired robot positions (shape) can be reached

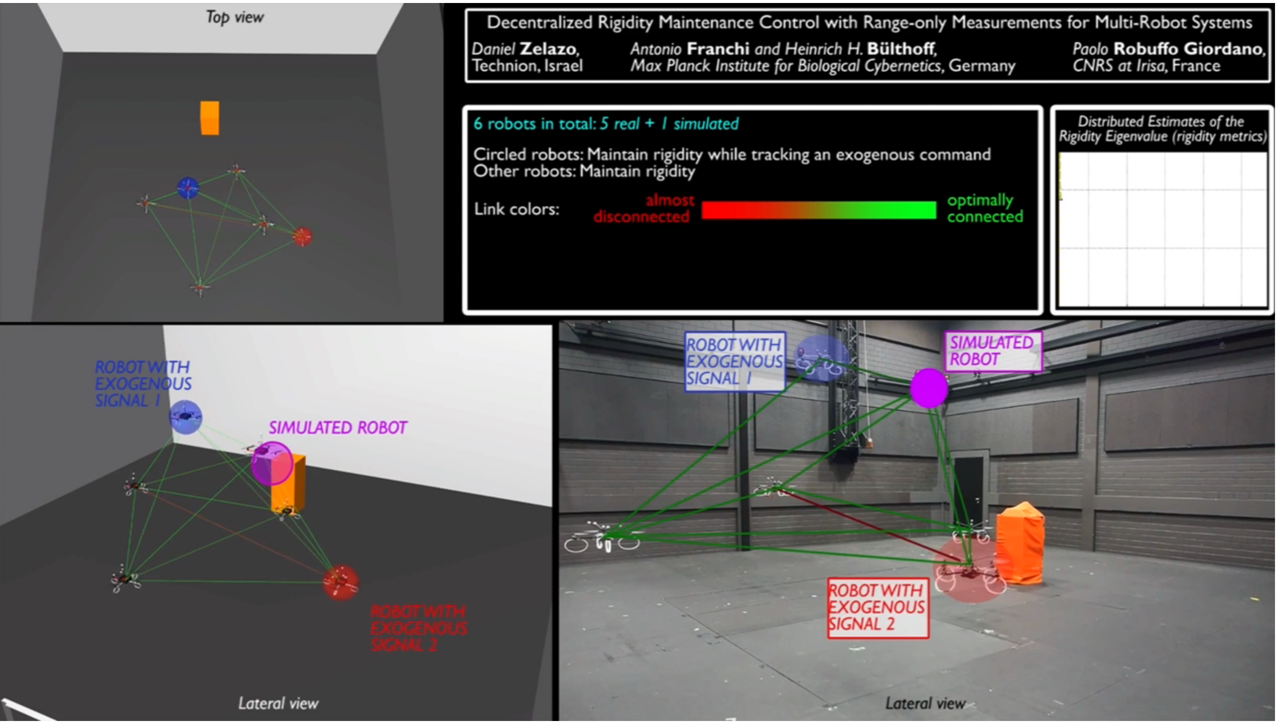


- **Relative localization** (in a common shared frame)
  - Measurement of inter-robot constraints =
    the current robot positions (shape) can be reconstructed

- And, again, no need of a complete interaction graph
  - Linear complexity $O(N)$ vs. quadratic complexity $O(N^2)$



Rigidity Maintenance with Distance Constraints



Decentralized Rigidity Maintenance Control with Range-only Measurements for Multi-Robot Systems

Daniel **Zelazo**, Technion, Israel
Antonio **Franchi** *and Heinrich H.* **Bülthoff**, *Max Planck Institute for Biological Cybernetics, Germany*
Paolo **Robuffo Giordano**, *CNRS at Irisa, France*

6 robots in total: 5 real + 1 simulated

Circled robots: Maintain rigidity while tracking an exogenous command
Other robots: Maintain rigidity

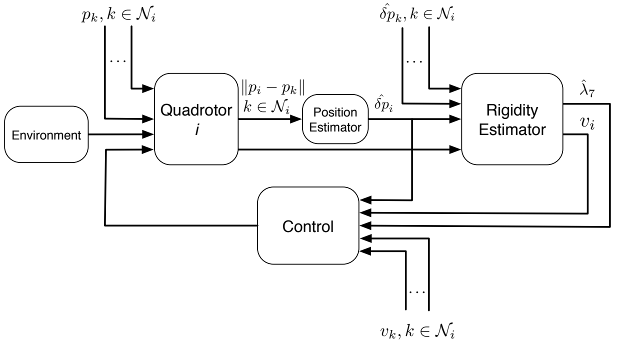
Link colors: almost disconnected — optimally connected

Distributed Estimates of the Rigidity Eigenvalue (rigidity metrics)

- Rigidity Matrix $\mathcal{R}(x)$

(~ Laplacian matrix $L(x)$)

- “Rigidity eigenvalue” λ_7
- Gradient-like control $\boxed{u_i \approx \frac{\partial \lambda_7}{\partial x_i}}$
- Decentralized implementation



- Rigidity controller maintains formation rigidity
- Decentralized estimation of relative positions from measured relative distances
- Relative positions used by the rigidity controller

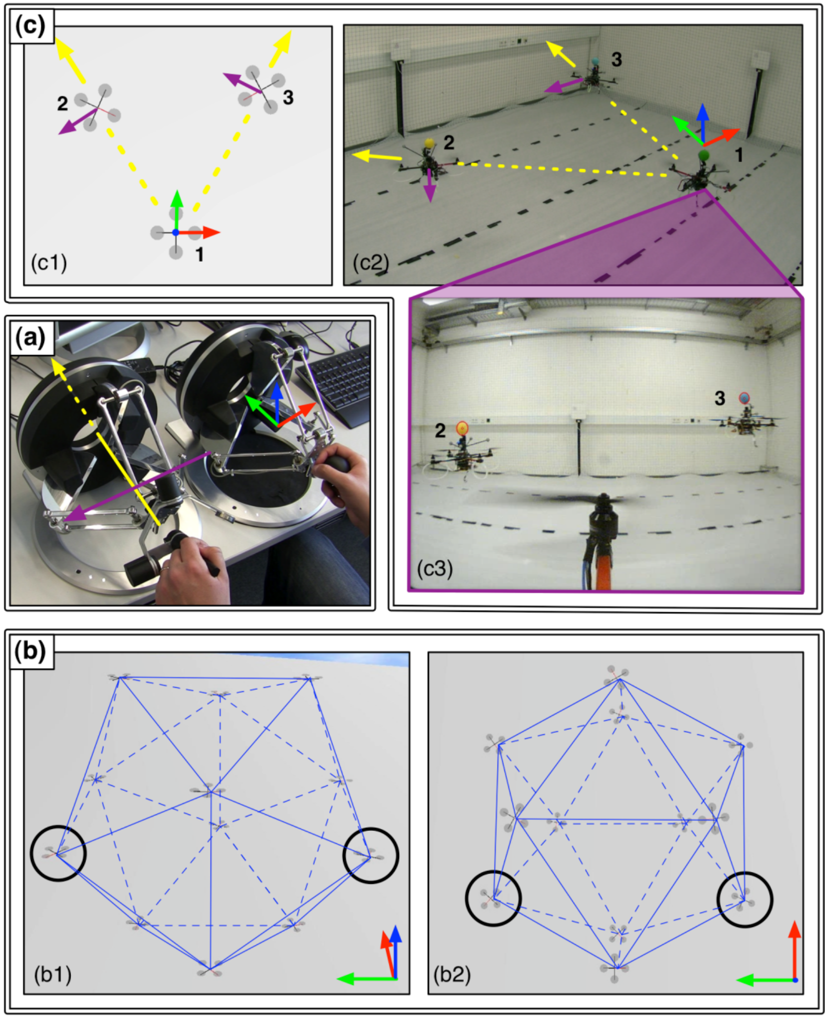
CDC 2012, RSS 2012,
CDC 2015, IJRR 2015

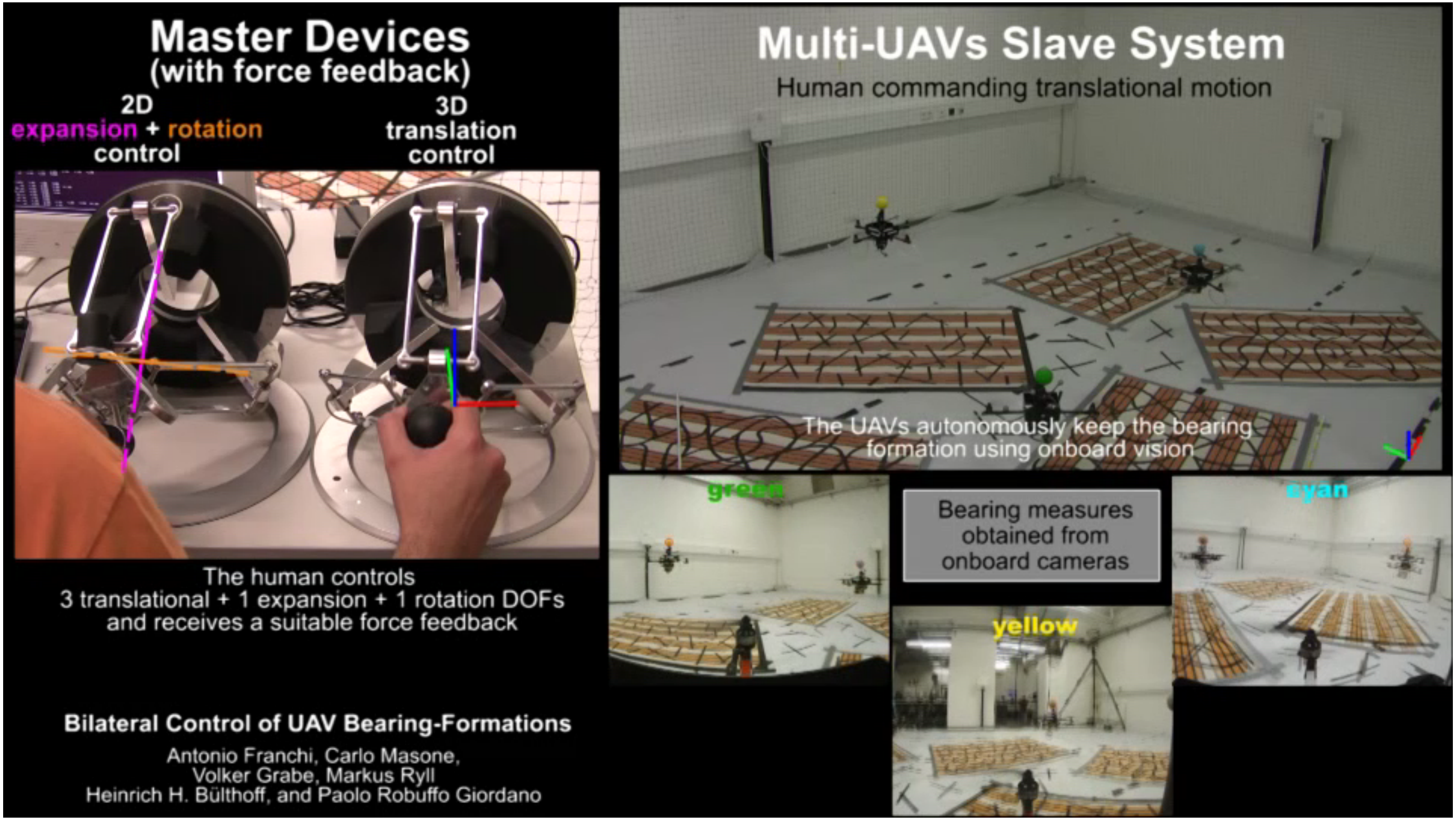
Constant Topology using Bearings

- Use relative bearings (unit vectors in 3D) 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





Master Devices
(with force feedback)

The human controls
3 translational + 1 expansion + 1 rotation DOFs
and receives a suitable force feedback

Bilateral Control of UAV Bearing-Formations

Antonio Franchi, Carlo Masone,
Volker Grabe, Markus Ryll
Heinrich H. Bülthoff, and Paolo Robuffo Giordano

Multi-UAVs Slave System

Human commanding translational motion

The UAVs autonomously keep the bearing
formation using onboard vision

Bearing measures
obtained from
onboard cameras

- The free dofs of a formation of UAVs are controlled by a human operator
- The instantaneous mismatch between commands (in terms of changes in formation shape) and actual motion becomes a force cue

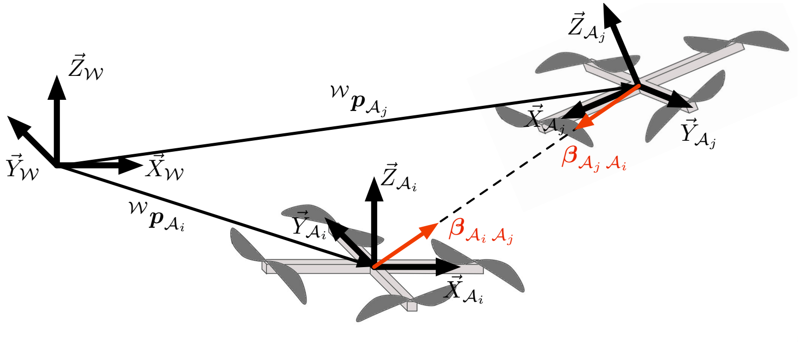
IJRR 2012

Bearing Rigidity Maintenance

- Similarly to the distance case, one can also define a notion of Bearing Rigidity

- Fundamental property for ensuring convergence of formation control and relative localization from measured bearings
  - If the formation is (bearing-)rigid, one can recover the relative pose of each robot in a common frame (up to a scalar factor)

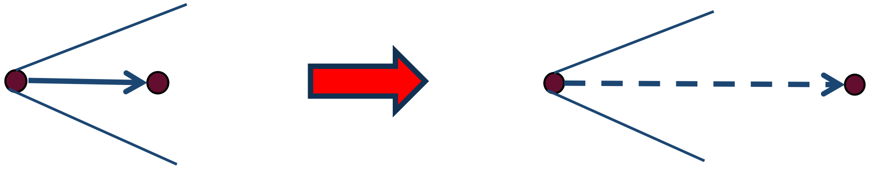
- Similar characterization via the spectral properties of a Bearing Rigidity Matrix $\mathcal{B}_{\mathcal{G}}$
  - However, the bearing case is more involved because bearings are vector measurements
    - must take care of which frame the bearings are expressed in (usually body-frame of each agent)
  - Also: they are (usually) non-reciprocal measurements because of the camera limited fov (directed sensing topology)



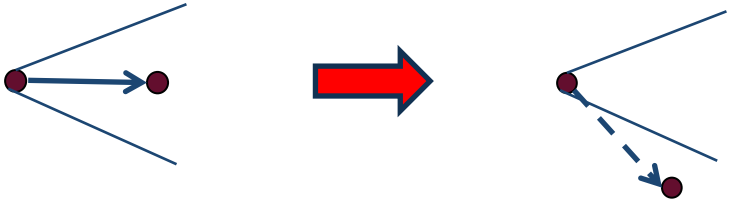
Bearing Rigidity Maintenance

- Maintenance action based on the maximization of the sixth smallest eigenvalue λ_6 of $\boldsymbol{\mathcal{B}}_{\mathcal{G}}^T \boldsymbol{\mathcal{B}}_{\mathcal{G}}$
  - Indeed, a framework in $\mathbb{R}^3 \times \mathcal{S}^1$ is bearing rigid iff $\mathrm{rank}(\boldsymbol{\mathcal{B}}_{\mathcal{G}}) = 4N - 5$

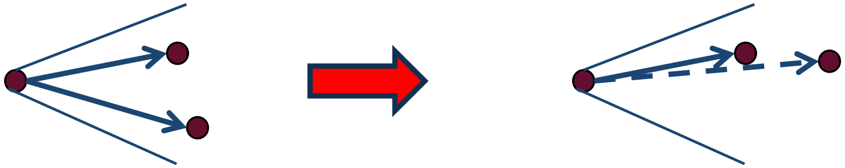
- Possibility to include several sensing/communication constraints among robot pairs:
  - Maximum/minimum range



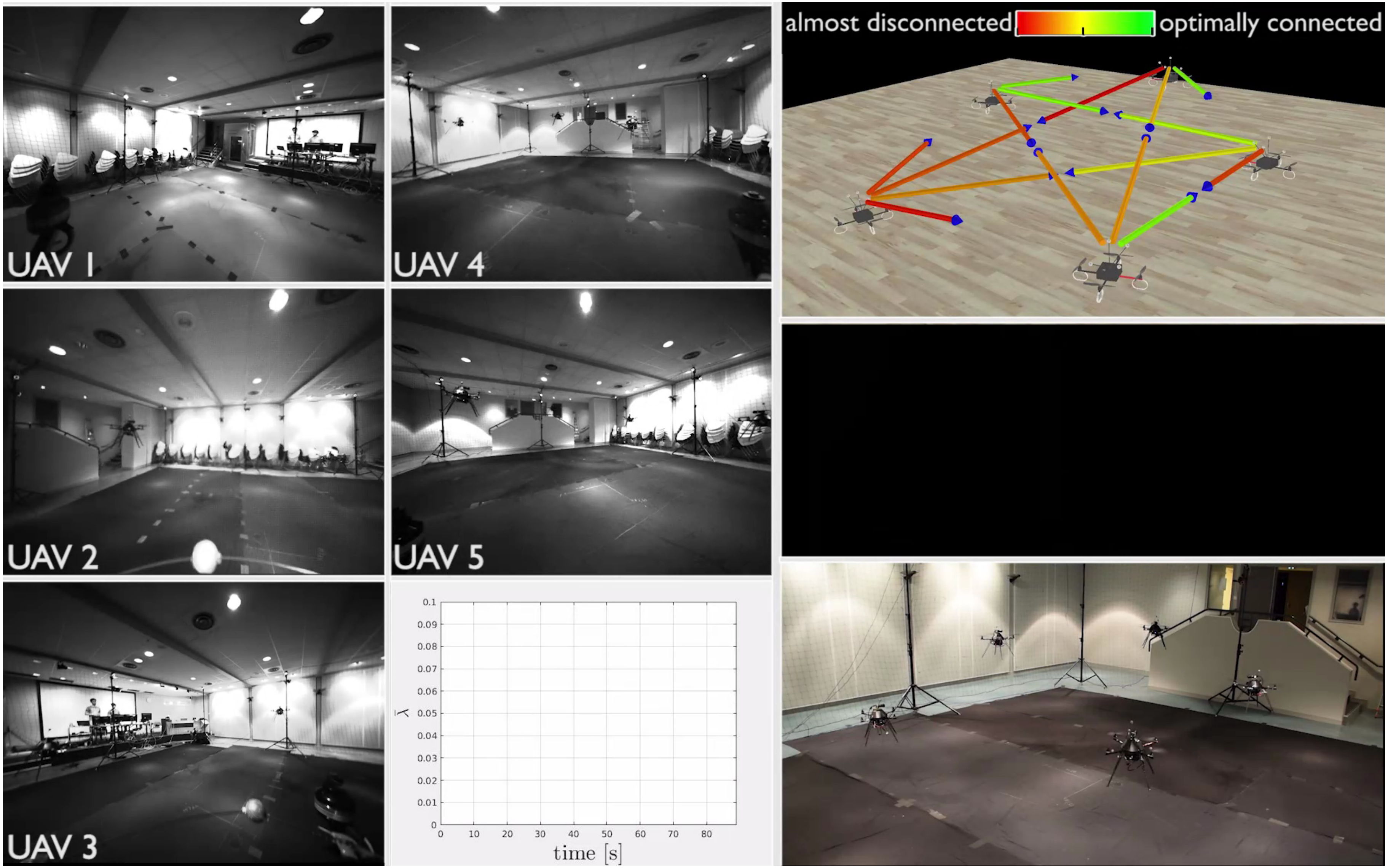
  - Limited field of view



  - Occluded visibility

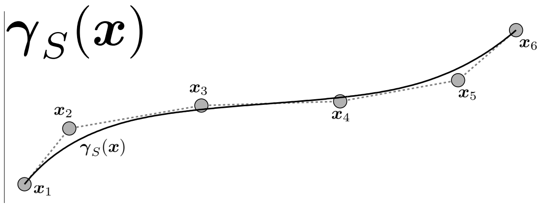


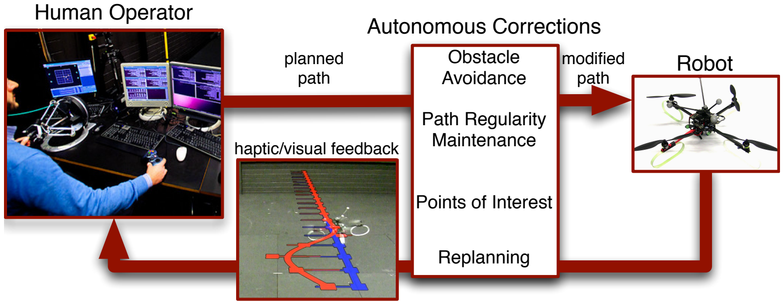
Bearing Rigidity Maintenance



Shared control with integral feedback

- Parametric path $\gamma_S(\boldsymbol{x})$




Human Operator

Autonomous Corrections

planned path

Obstacle Avoidance

Path Regularity Maintenance

Points of Interest

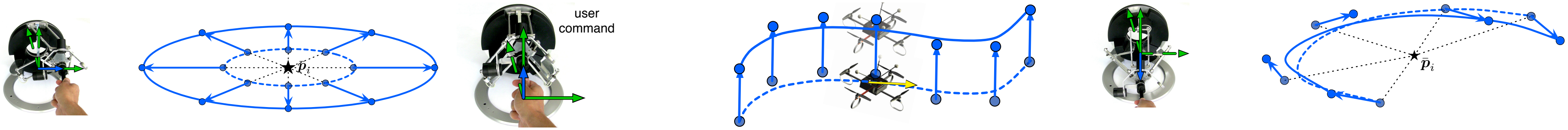
Replanning

modified path

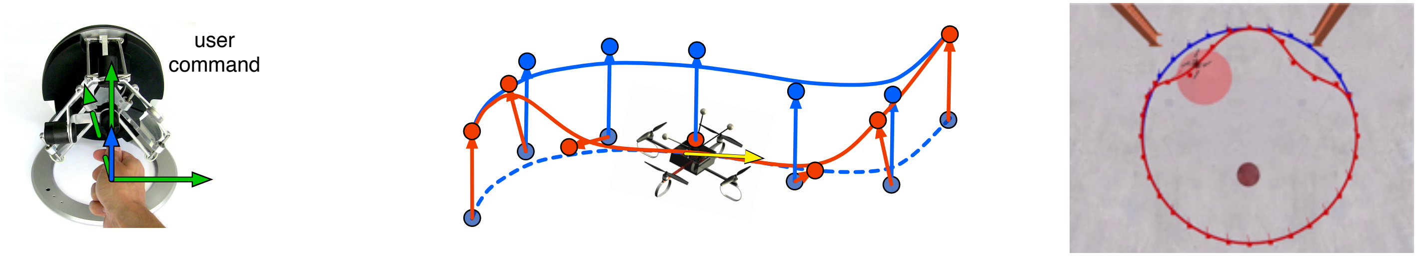
Robot

haptic/visual feedback

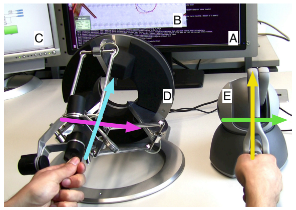
- The human user can modify some global properties of the path



- An autonomous corrector takes care of dynamic feasibility and obstacle avoidance

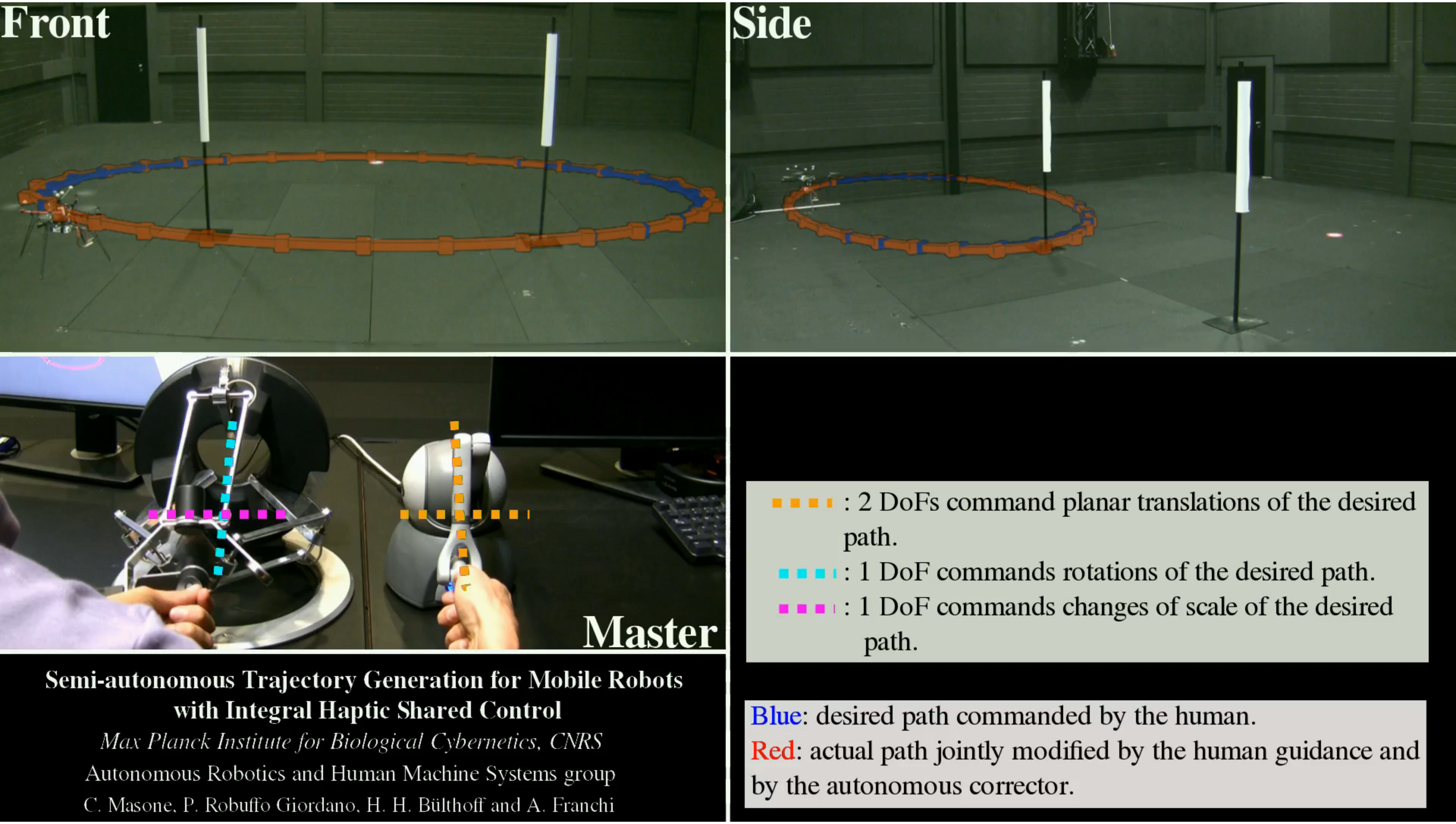


- Haptic cues proportional to the integral mismatch between commanded (blue) and actual (red) paths
  - Can inform about future consequences of human operator's actions



IROS 2012, ICRA 2014, IJRR (under review)

Shared control with integral feedback



Semi-autonomous Trajectory Generation for Mobile Robots with Integral Haptic Shared Control

Max Planck Institute for Biological Cybernetics, CNRS

Autonomous Robotics and Human Machine Systems group

C. Masone, P. Robuffo Giordano, H. H. Bülthoff and A. Franchi

🟧🟧🟧 : 2 DoFs command planar translations of the desired path.

🟦🟦🟦 : 1 DoF commands rotations of the desired path.

🟪🟪🟪 : 1 DoF commands changes of scale of the desired path.

Blue: desired path commanded by the human.

Red: actual path jointly modified by the human guidance and by the autonomous corrector.

IROS 2012, ICRA 2014

Future Perspectives

- From “partially controlled” lab conditions…

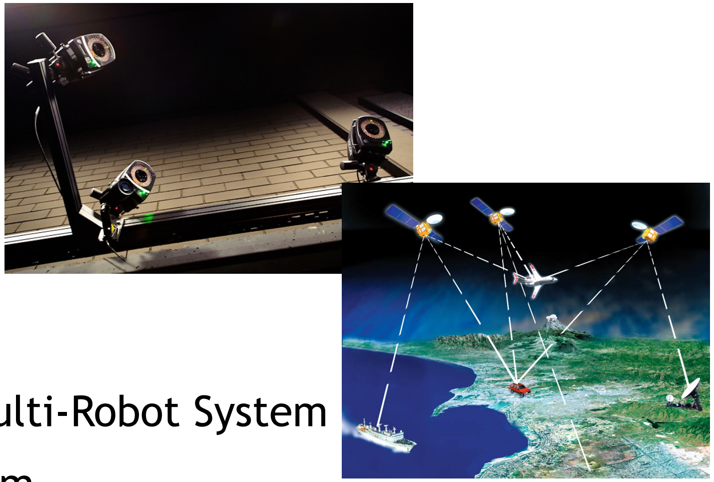
…to real-world scenarios

- Address (complex) challenges on perception/decision making
  - Rely on “own” skills such as local sensing/communication
  - Avoid “global/centralized” aids (common ref frame, knowledge of global group properties)
  - Sensory limitations (state-dependent constraints such as, e.g., occlusions, max range)
  - Multi-robot redundancy for dealing with individual sensor limitations

Future Perspectives

- Example: shared exploration of “complex” environments with a team of ground/flying robots

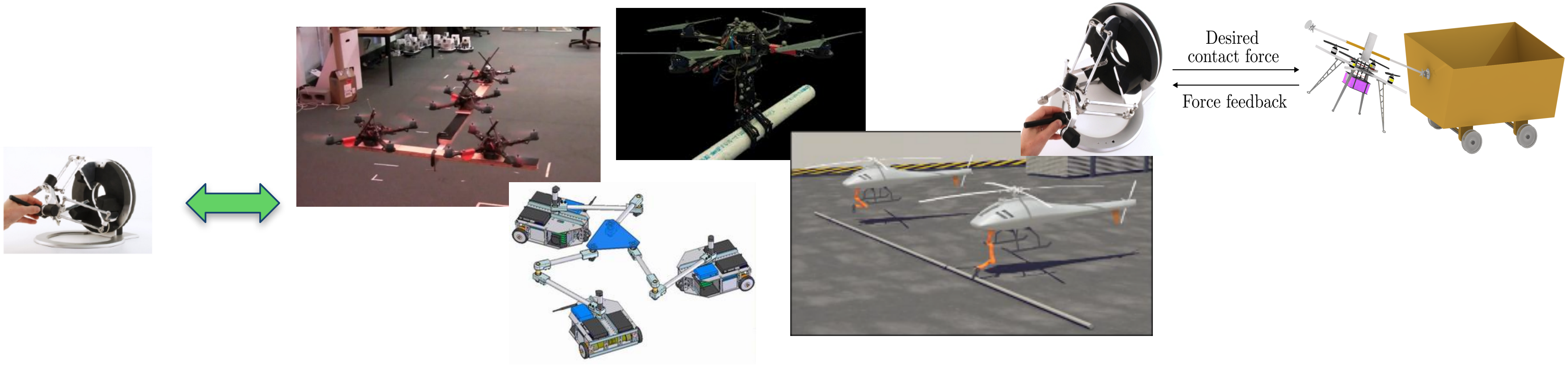
- Use of onboard sensing (mainly vision) and inter-robot communication for:
  - robust navigation (obstacle avoidance, state estimation, detection of other robots in the scene)
  - formation control (keeping a desired spatial arrangement)
  - flexible maintenance of global properties (connectivity, rigidity)



- ANR JC Project **SenseFly** (2015-2018) Sensor-Based Flying Multi-Robot System
  - Exploit group of quadrotors as “portable GPS/Vicon” system
  - Provide flexible “localization services”

Future Perspectives

- Extend the results from navigation/exploration tasks to **interaction with the environment**
  - Manipulation, transportation, grasping, etc.



- Some active groups (LAAS, DLR, SNU, ANU)

- Exciting times ahead of us !

Acknowledgments

thanks to my collaborators

A. Franchi

LAAS, Toulouse, France

C. Secchi

Università di
Modena e Reggio Emilia

D. Zelazo

Technion, Israel

D.J. Lee

Seoul National University

H. I. Son

Samsung, South Korea

R. Spica

Stanford

F. Schiano

INRIA

Thanks to the audience!