Towards Autonomous-collaborative and Haptic-tele-operated UAVs with Fully-onboard State Estimation and Physical Interaction Capabilities

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This talk will provide a high-level overview of some of the very recent and current activities of the Autonomous Robotics and Human-Machine Systems group at the MPI for Biological Cybernetics. The talk will also give a perspective about future challenges in the aerial collaborative robotics and haptic teleoperation field, with particular emphasis on onboard state estimation and physical interaction capabilities.

The main research activities of the group are centered around the study and design of autonomous robotic systems evolving in an uncertain and dynamical world and interacting with people, and from a control-oriented perspective. The group activity can be divided into two main areas:

- Algorithms for collaborative autonomous control
- Algorithms for human interaction through interfaces.

I. Algorithms for Collaborative Autonomous Control

A. Vision-based formation stabilization

In this work we considered the problem of controlling the motion of a group of UAVs bound to keep a formation defined in terms of only relative angles (i.e., a bearing-formation). This problem can naturally arise within the context of several multi-robot applications such as, e.g., exploration, coverage, and surveillance. In [1] we introduced and thoroughly analyzed the concept and properties of bearing-formations, and provided a class of minimally linear sets of bearings sufficient to uniquely define such formations. We then proposed a bearing-only formation controller requiring only bearing measurements, converging almost globally, and maintaining bounded inter-agent distances despite the lack of direct metric information. The controller still leaves the possibility to impose group motions tangent to the current bearing-formation. These can be either autonomously chosen by the robots because of any additional task (e.g., exploration), or exploited by an assisting human co-operator. We have proven the effectiveness of the approach with experiments involving group of quadrotor UAVs endowed with onboard cameras, see Fig. 1. Along this line an extension of this control strategy that make use of distributed estimation has been presented in [2].

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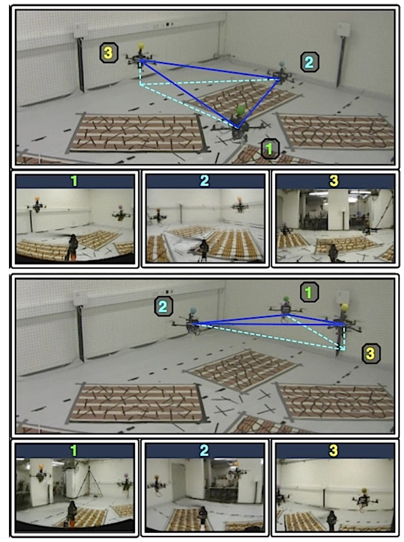


Fig. 1. Bearing(camera)-based autonomous formation control with aerial vehicles.

B. Graph-theoretical methods for controlling mobile networks of robots

In this area we designed decentralized controllers based on graph-theoretical methods in order to control a group of mobile robots while coping with the typical constraints on the inter-robot sensing/communication capabilities. In [3] we proposed a novel decentralized strategy able to enforce connectivity maintenance for a group of robots in a flexible way, that is, by granting large freedom to the group internal configuration so as to allow establishment/deletion of interaction links at anytime as long as global connectivity is preserved. A peculiar feature of that approach was that we embedded into a unique connectivity preserving action a large number of constraints and requirements for the group: (i) presence of specific inter-robot sensing/communication models, (ii) group requirements such as formation control, and (iii) individual requirements such as collision avoidance. This is achieved by defining a suitable global potential function of the second smallest eigenvalue of the graph Laplacian, and by computing, in a decentralized way, a gradient-like controller built on top of this potential. A related graph-theoretical method that is useful to maintain the rigidity of the group has been proposed in [4]. Two screenshots of some experiments on rigidity maintenance are shown in Fig. 2.

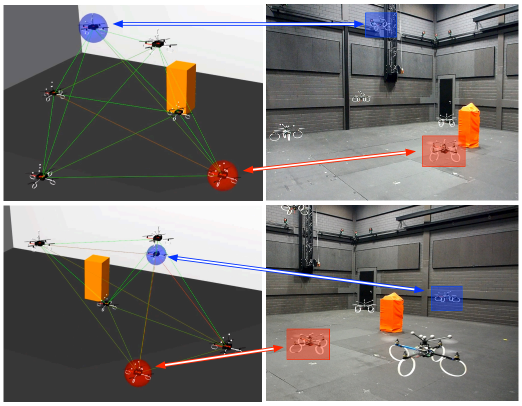


Fig. 2. Autonomous Rigidity maintenance in a group of 6 quadrotor UAVs.

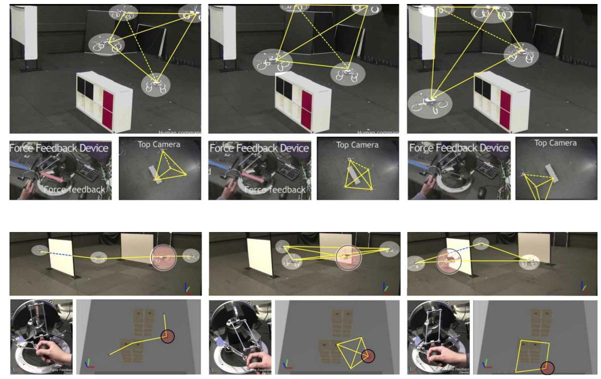


Fig. 4. Experiments of shared control of multiple mobile robots. Fixed Topology versus time-varying topology case.

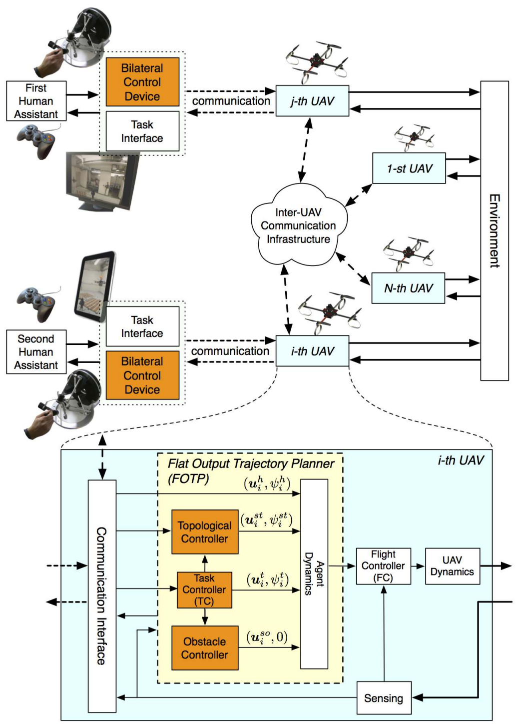


Fig. 3. Architecture and overall framework of the framework on shared control of multiple mobile robots.

II. Algorithms for Human Interaction Through Interfaces

In these studies we aimed at designing original and effective ways to let humans co-operate with complex groups of semi-autonomous robotic systems.

A. Shared Control with Multiple Mobile Robots

In this work we addressed the problem of the interaction between humans and groups of robots whose local synergy is exploited to accomplish complex tasks. Multi-robot systems possess several advantages w.r.t. single robots, e.g., higher performance in simultaneous spatial domain coverage, better affordability as compared to a single/bulky system, robustness against single point failures. The interested reader is referred to [5] for a high-level overview of the approach (see Fig. 3 for an overview of the idea).

As multi-robot platform, we considered the case of a group of Unmanned Aerial Vehicles (UAVs), because of their high motion flexibility and potential pervasiveness in dangerous or unaccessible locations. We envisioned a scenario where the UAVs possess some level of local autonomy and act as a group, e.g., by maintaining a desired formation, by avoiding obstacles, and by performing additional local tasks. At the same time, the remote human operator is in control of the overall UAV motion and receives, through haptic feedback, suitable cues informative enough of the remote UAV/environment state. We addressed two distinct possibilities for the human/multi-robot teleoperation: a top-down approach, and a bottom-up approach, mainly differing in the way the local robot interactions and desired formation shape are treated, see Fig. 4 for a comparison of the two approches.

The fixed-topology approach has been considered in [6] where the N UAVs are abstracted as 3-DOF first-order kinematic VPs (virtual points): the remote human user teleoperates a subset of these N VPs, while the real UAV's position tracks the trajectory of its own VP. The VPs collectively move as an N-nodes deformable flying object, whose shape (chosen beforehand) autonomously deforms, rotates and translates reacting to the presence of obstacles (to avoid them), and the operator commands (to follow them). The operator receives a haptic feedback informing him about the motion state of the real UAVs, and about the presence of obstacles via their collective effects on the VPs. Passivity theory is exploited to prove stability of the overall teleoperation system. In [7], [1] the approach has been extended to the case where bearing measurements are the only available. The main focus in that case have been the design of a novel decentralized and minimum-complexity bearing-only formation controller for the slave side. In [8] we proposed an experimental testbed for the intercontinental teleoperation of multiple UAVs and demonstrated its feasibility employing a communication channel going from Germany to South Korea.

The time-varying topology approach has been firstly proposed in [9] where the N UAVs are abstracted as 3-DOF

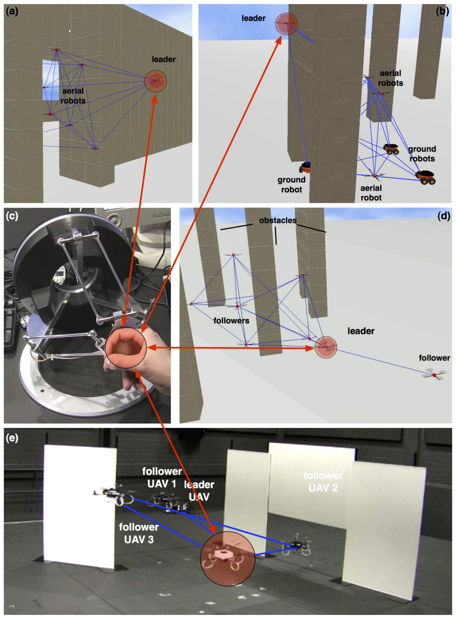
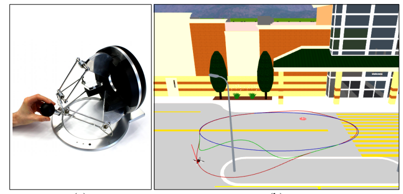


Fig. 5. Simulations and experiments of shared control of multiple heterogeneous mobile robots.

second-order VPs: the remote human user teleoperates a single leader, while the remaining followers motion is determined by local interactions (modeled as spring/damper couplings) among themselves and the leader, and repulsive interactions with the obstacles. The overall formation shape is not chosen beforehand but is a result of the UAVs motion. Split and rejoin decisions are allowed depending on any criterion, e.g., the UAVs relative distance and their relative visibility (i.e., when two UAVs are not close enough or obstructed by an obstacle, they split their visco-elastic coupling). The operator receives a haptic feedback informing him about the motion state of the leader which is also influenced by the motion of its followers and their interaction with the obstacles. Passivity theory is exploited to prove stability of the overall teleoperation system. The first journal paper about the time-varying topology approach is [10] and its results are general enough to be applied to systems of heterogenous mobile robots (see Fig. 5). In [11] the approach has been extended by explicitly consider the presence of time delays, both among the haptic device and the multi-robot system, and within the robots composing the multi-robot system. In [12] we presented a decentralized passivity-based control strategy for the bilateral teleoperation of a fleet of Unmanned Aerial Vehicles (UAVs). The human operator at the master side can command the fleet motion and receives suitable force cues informative about the remote environment. By properly controlling the energy exchanged within the slave side (the UAV fleet), the algorithm guaranties that the connectivity of the fleet is preserved and we prevent inter-agent and obstacle collisions. At the same time, the behavior of the UAVs is allowed to be as flexible as possible with arbitrary split and join maneuvers. The results of the paper are validated through semi-experiments. An experimental validation of the bottom-up approach has been presented in [13], while in [14] an extension of the approach where the group autonomously changes the leader in order to maximize the performances is presented.



(a) (b)

Fig. 6. Simulations of the interactive planning framework.

B. *Interactive Planning*

The framework of bilateral shared control of mobile robots has been then extended with the aim of increasing the robot autonomy and decreasing the operator commitment. We considered persistent autonomous behaviors where a certain trajecotry has to be executed by the robot. The human operator is in charge of modifying online some geometric properties of the desired trajectory. This is then autonomously processed by the robot in order to produce an actual path guaranteeing: i) tracking feasibility, ii) collision avoidance with obstacles, iii) closeness to the desired path set by the human operator, and iv) proximity to some points of interest. A force feedback is implemented to inform the human operator of the global deformation of the path rather than using the classical mismatch between desired and executed motion commands. The method has been presented in [15], see Fig. 6 for an illustration.

III. Current and Future Challenges

The current work of the group is focused on two main research areas: aerial physical interaction and haptic teleoperation with full-onboard aerial estimation and control. In the aerial physical interaction field we recently studied the problem of planning a trajectory that connects two arbitrary states while allowing a quadrotor UAV to grasp a moving target at some intermediate time. A preliminary work in this promising field of research has been presented in [16]. In that work, two classes of canonical grasping maneuvers are defined and characterized. A planning strategy relying on differential flatness is then proposed to concatenate one or more grasping maneuvers by means of spline-based sub-trajectories, with the additional objective of minimizing the total transfer time. The proposed planning algorithm is not restricted to pure hovering-to-hovering motions and takes into account practical constraints, such as the finite duration

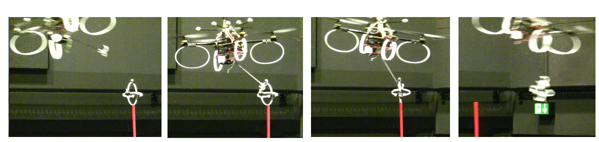


Fig. 7. Aerial grasping with a quadrotor UAV.

of the grasping phase. Figure 7 show some screenshots from an experimental validation of the approach.

Finally, the talk will provide also an insight on the future challenges addressed by the recent still unpublished results in the last two areas. In particular it will show some results on RGBD-camera-based haptic teleoperation [17] and on a control strategy that allows a quadrotor UAV to stably exert a given 3D force on the environment [18].

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