

Interactive Demo: Haptic Remote Control of Multiple UAVs with Autonomous Cohesive Behavior

Thomas Nestmeyer, Martin Riedel, Johannes Lächele, Simon Hartmann, Fiete Botschen,
Paolo Robuffo Giordano, and Antonio Franchi

In this interactive demo we show the bilateral teleoperation of a group of Unmanned Aerial Vehicles (UAVs). The experimental setup involves the following three environments physically separated in space. An illustrative overview is given in Fig. 1:

- 1) the *multi-robot site* at the Max Planck Institute for Biological Cybernetics in Tübingen, where the multi-robot system is present;
- 2) the *operator site* in the Conference Center of Karlsruhe, where two human operators can (independently) act on two haptic interfaces;
- 3) a standard *internet link* between Karlsruhe and Tübingen based on the Virtual Private Network technology (VPN): this is prone to packet loss, jittering and time delays.

The setup used in this demo represents an extension of the one used to perform intercontinental teleoperation from Korea to Germany, and presented in [1]. First of all, in the current demo we are using multiple operators and multiple haptic interfaces instead of just one. Additionally, in [1] the UAVs were forced to maintain a fixed topology based on inter-distances and therefore topological changes were not allowed to happen.

In this demo, topological changes from the UAV side are allowed as long as the generalized connectivity is preserved (see [2] for the details). The reader that is interested to completely unconstrained topological behaviors is instead referred to [3]. Finally, a general overview on the broad topic of *shared control of multiple mobile robots* can be found in [4].

A. Connectivity Maintenance

The difference between a group of many single robots and a multi-robot system is the ability to communicate and then cooperate together towards a common objective. In this sense, parallelizing the execution of several small tasks forming together a complex mission is a fundamental component of successful multi-robot applications. A major problem when dealing with multiple robots is to ensure a decentralized design of the control algorithms, as this

requirement guarantees a fail-safe behavior and an upper limit on the amount of needed computational resources. Decentralization implies that every robot only relies on its own perception and the data transmitted from its “neighbors” (robots that are in close proximity, i.e., with which the robot can communicate via, typically, only “one hop”). Several decentralized algorithms are usually run in parallel by our multiple robot system for obtaining the desired behavior.

Most decentralized algorithms locally estimate global properties of the whole multi-robot system, global properties which are needed to implement complex control laws. In order to achieve this goal, the underlying graph topology must (at least) be connected in the usual sense that any pair of robots can exchange information over a multi-hop communication. To ensure this constraint, one can either stick to fixed group topologies, where no links can be broken or restored. An alternative is to resort to more flexible methods as the one presented in [2] where connectivity is always maintained in a decentralized way, but links can continually be broken or established over time. On top of that, inter-robot and obstacle collisions can also be avoided by enforcing loss of connectivity whenever a robot gets too close to another robot or another obstacle. Sensing constraints, such as inter-robot visibility, can also be seamlessly taken into account. This framework has been denoted as *generalized connectivity*. The main steps of this method are the following: each robot estimates the second smallest eigenvalue λ_2 and its corresponding component of the normalized eigenvector of the graph Laplacian. For this eigenvalue, also known as the Fiedler eigenvalue, it holds that $\lambda_2 > 0$ if and only if the graph is connected. Introducing a potential function on λ_2 that grows unbounded when coming close to some lower bound $\lambda_2^{\min} \geq 0$, a gradient controller can always ensure that $\lambda_2 > \lambda_2^{\min}$ and, therefore, connectivity is guaranteed. For more information, the reader is referred to [2], where additional analysis on the stability (passivity) of the closed-loop are detailed.

B. The Multi-robot Site

The multi-robot site consists of a group of four quadrotor UAVs that are highly customized versions of the MK-Quadro¹ platform. Each quadrotor has a diameter of 0.5 m and runs TeleKyb, a software framework for the high-

T. Nestmeyer, M. Riedel, J. Lächele, S. Hartmann, F. Botschen and A. Franchi are with the Max Planck Institute for Biological Cybernetics, Spemannstraße 38, 72076 Tübingen, Germany. E-mail: {thomas.nestmeyer, martin.riedel, johannes.laechele, simon.hartmann, fiete.botschen, antonio.franchi}@tuebingen.mpg.de.

P. Robuffo Giordano is with the CNRS at IRISA Rennes, Campus Universitaire de Beaulieu, 35042 Rennes cedex, France. E-mail: prg@irisa.fr.

¹<http://www.mikrokoetter.de/>

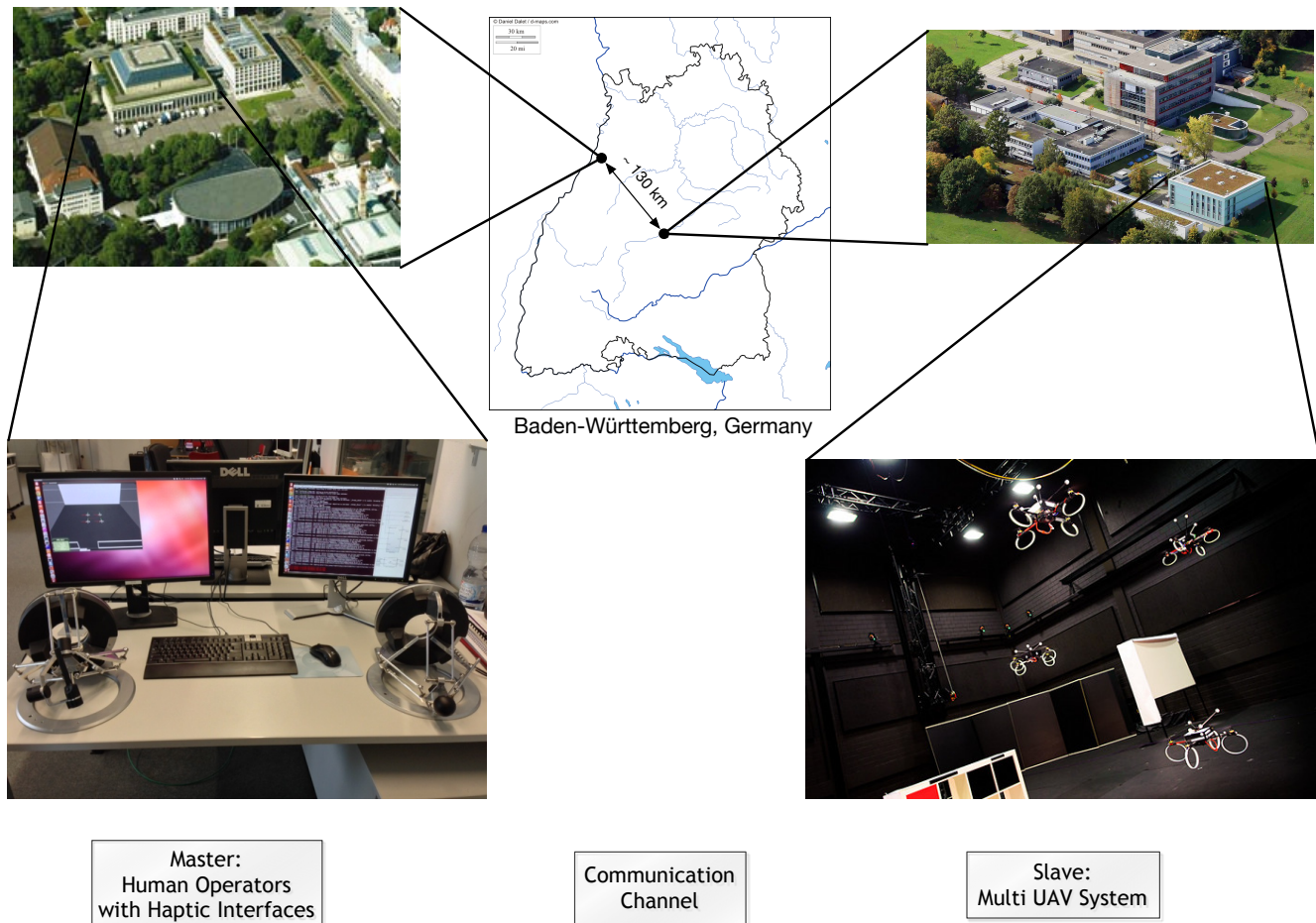


Fig. 1: Illustrative overview of the master-slave-system used in the bilateral teleoperation demo between Karlsruhe (master) and Tübingen (slave).

level motion control also presented in this workshop². The quadrotors are free to move in an area of about $10 \times 10 \times 4$ m (called Tracking Lab) located in the Max Planck Institute for Biological Cybernetics in Tübingen. The area is provided with a motion capturing system³ that allows to retrieve both the position and orientation of the quadrotors with high precision. The estimation of the full state of the quadrotors is also complemented with onboard IMU measurements. The current position, velocity, and orientation of the quadrotor is sent to the operator site. Two robots have a down facing camera: the corresponding videos are streamed to the operator site.

C. The Operator Site

At the operator site in Karlsruhe two haptic force-feedback devices are provided: the Omega legacy (precursor of the Omega.3) and Omega.6⁴: these can be independently controlled by two human operators. The two devices have 3 actuated degrees of freedom which are used by each operator

to control the motion of one of the UAVs. A local control algorithm computes the forces applied to the two devices in order to generate a 3-dimensional haptic feedback for the operators. The 3-dimensional input of each device is used as a velocity reference for one of the four UAVs. The two controlled UAVs then try to follow the human reference as long as this does not conflict with the generalized connectivity maintenance. The remaining two quadrotors help the group to stay connected, thus enabling the human controlled robots a wider range of motion. The human operators are finally asked to find some objects in the area by using the video feedback from the down facing camera.

The video feedback is subject to higher delays compared to the position, velocity and orientation signals. This is due to the larger amount of data needed to transport the video stream. In addition to the video feedback, the operator is provided with the force feedback in order to feel the influence of the generalized connectivity maintenance algorithm on the motion of the commanded robot more quickly. For example this happens whenever: (i) the commanded UAV comes close to an obstacle (or another robot), (ii) a link crucial for the connectivity reaches its maximum distance. Although the operator can counteract this force and keep pushing to, e.g.,

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³<http://www.vicon.com/>

⁴<http://www.forcedimension.com/>

steer the robot into a wall or trying to break a link, in the end the continual connectivity will prevent the robot from crashing or breaking that link.

Stability of the haptic device is guaranteed by suitably choosing the damping factor in the force controller. This simple strategy is enough to handle the typical delays in the Karlsruhe-Tübingen internet connection. More sophisticated algorithms can be used in the case of more critical connections, see, e.g., [5], [6].

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