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Human-Collaborative Schemes in the Motion Control of Single and Multiple Mobile Robots

Antonio Franchi¹

Abstract—In this chapter we show and compare several representative examples of human-collaborative schemes in the control of mobile robots, with a particular emphasis on the aerial robot case. We first provide a simplified yet descriptive model of the robot and its interactions. We then use this model to define a taxonomy that highlights the main aspects of these collaboration schemes, such as: the physical domain of the robots, the degree of autonomy, the force interaction with the operator (e.g., the unilateral versus the bilateral haptic shared control), the near-operation versus the teleoperation, the contact-free versus the physically interactive situation, the use of onboard sensors, and the presence of a time-horizon in the operator reference. We then specialize the proposed taxonomy to the multi-robot case in which we further distinguish the methods depending on their level of centralization, the presence of leader-follower schemes, of formation control schemes, the ability to preserve graph theoretical properties, and to perform cooperative physical interaction. The common denominator of all the examples presented in this chapter is the presence of a human operator in the control loop. The main goal of the chapter is to introduce the reader and provide a first-level analysis on the several ways to effectively include human operators in the control of both single and multiple aerial robots and, by extension, of more generic mobile robots.

I. INTRODUCTION

A mobile robot is primarily a machine that is able to perceive the surrounding environment and move in it in a safe and effective way for the humans, for itself, and for the given objective. The ability to automatically control its own motion, at both the higher level (guidance, planning) and the lower one (navigation and servoing), constitutes one of the fundamental building blocks of the sought robot autonomy. However, robots, which in general do not exist and operate isolated from humans, can actually improve their effectiveness in achieving the given task by means of a well-designed human-collaborative control schemes. Analyzing and properly designing the way to achieve an optimal human collaboration is therefore a crucial aspect in order to attain a fully mature robotic system that is able to operate in a complex and real world.

In this chapter we show and compare several ways to effectively design the collaborative control. We do so by first introducing a simple yet descriptive model for the robots and the human interfaces. We then propose a list of what we consider fundamental axes for a proper classification of the collaborative scheme, namely the

- *physical domain of the robots* as, e.g., whether they are operating and moving on the ground or in the air;

- *degree of autonomy from the human operator*, i.e., at which level and with which frequency the human operator is involved in influencing the robot motion, in particular, in this chapter we mainly focus on the so called ‘shared control’ case. Within this case we further specialize our taxonomy depending on the *presence of a time-horizon in the reference* that is sent by the operator to the robots.
- *kind force interaction with the operator*, i.e., whether the collaboration involves or not mechanical interaction and haptics and in which direction (forward-force, feedback-force (bilateral), unilateral);
- *near-operation versus the teleoperation*;
- *amount of physical interaction with the environment*;
- *use of onboard sensors*;

The proposed taxonomy is then further specialized in the case of the use of multiple robots, for which we introduce an additional axes, namely the

- *level of centralization*;
- use of a scheme of the kind *master-leader-followers*;
- use of a scheme of the kind *formation-orthogonal*;
- use of a scheme of the kind *global property preservation*;
- *ability to perform cooperative physical maneuvers*.

The common denominator of all the axes presented in this chapter is the presence of a human operator in the control loop. In fact, fully autonomous control algorithms are not in general easy to extend in order to cope with (and to exploit) the presence of a human operator. The main goal of the chapter is therefore to introduce the reader to the several ways to effectively include human operators in the control of both single and multiple aerial mobile robots, and to provide a first-level analysis on these systems. A particular emphasis is set on the aerial robots case, which is at date not yet fully explored and understood, and is among the most challenging cases. Nevertheless, all the presented aerial robotics schemes are easily transferable to many other mobile robot as well.

II. MODELING OF THE ROBOT AND THE INTERACTIONS

In this section we provide a formal description of the robot and its interactions. The main goal is to introduce a standard model and a nomenclature that is convenient for the description of human-collaborative schemes like the ones that we illustrate in this chapter. For the sake of completeness, the notation introduced goes beyond the examples included in the taxonomy proposed in the next sections.

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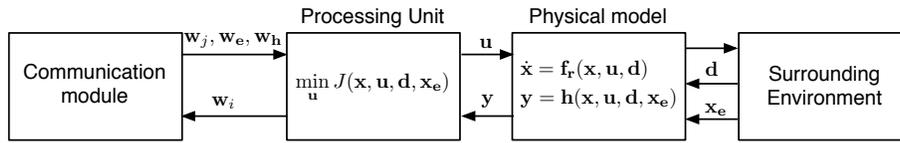


Fig. 1: High-level model of the i -th mobile robot.

A. Mobile Robot

A *mobile robot* can be viewed as a mechanical system possessing some degrees of freedom (DoFs) that is equipped with actuators, sensors, a processing unit, a communication module, and a mathematical model of itself and the surrounding environment. The combination of all these components are used by the robot to control its own DoFs and, as a byproduct, to modify the state of the surrounding environment, in presence of external disturbances and uncertainties. We refer to Figure 1 for a high-level model of a mobile robot physically interacting and communicating with the surrounding environment.

The *configuration* of the $n_q \in \mathbb{N}$ DoFs of the robot is represented by a vector $\mathbf{q} \in \mathbb{R}^{n_q}$. The physical model of the robots is implicitly represented by a differential equation

$$\dot{\mathbf{x}} = \mathbf{f}_r(\mathbf{x}, \mathbf{u}, \mathbf{d}) \quad (1)$$

where $\mathbf{x} \in \mathbb{R}^{n_x}$ is the *physical state*, $\mathbf{u} \in \mathbb{R}^{n_u}$ is the *control input* (a signal that the processing unit can change arbitrarily and drives the robot actuators), and $\mathbf{d} \in \mathbb{R}^{n_d}$ is the *external input* (a signal that the is out of control to the robot and can represent both the interaction with the environment and the inaccuracies of the model). The vector \mathbf{x} includes the configuration \mathbf{q} and may include also its derivative, i.e., $\mathbf{x} = (\mathbf{q}^T \dot{\mathbf{q}}^T)^T$.

In presence of more than one robot we assume an index $i \in \{1, \dots, N\}$ being associated to each robot, where N is the total number of robots. We shall refer to the robot associated to i as the ' i -th robot' or the 'robot i '. The quantities corresponding to the i -th robot are added the subscript i , e.g., \mathbf{x} becomes \mathbf{x}_i , \mathbf{u} becomes \mathbf{u}_i , and so on so forth.

The sensors of a robot typically provide a partial information about the physical state, the external input, and the surrounding environment. This information is in general represented by the measurement function

$$\mathbf{y} = \mathbf{h}(\mathbf{x}, \mathbf{u}, \mathbf{d}, \mathbf{x}_e) \quad (2)$$

where $\mathbf{y} \in \mathbb{R}^{n_y}$ is the *measurement* and $\mathbf{x}_e \in \mathbb{R}^{n_{x_e}}$ is the *environment state*, which may include external objects, other robots as seen by the robot i , and a nearby human collaborator.

The *communication module* provides the robots additional signals that can be used by its processing unit to achieve their mission. A signal that comes from another robot j is denoted with $\mathbf{w}_j \in \mathbb{R}^{n_{w_j}}$, where $j \in \mathcal{N}_i$, being $\mathcal{N}_i \subseteq \{1, \dots, N\}$ the set of robots that communicate with the robot i (*communication neighbors*). A signal that comes from the human-robot interface is instead denoted with $\mathbf{w}_h \in \mathbb{R}^{n_{w_h}}$. A signal could come also from other sources (like, e.g., a smart

environment) in that case we denote it with $\mathbf{w}_e \in \mathbb{R}^{n_{w_e}}$. The communication module is also in charge of disseminating to each robot j , with $j \in \mathcal{N}_i$, the signal \mathbf{w}_i coming from the robot processing unit.

The *processing unit* implements a robot control algorithm that chooses \mathbf{u} in order to, typically, minimize an objective function

$$J(\mathbf{x}, \mathbf{u}, \mathbf{d}, \mathbf{x}_e, \{\mathbf{w}_j | j \in \mathcal{N}_i\}, \mathbf{w}_h, \mathbf{w}_e). \quad (3)$$

In order to do so, the robot control algorithm can rely on the following information:

- a model of the robot (e.g., (1)) and a model of the environment
- the measurement \mathbf{y}
- the communicated signals $\{\mathbf{w}_j | j \in \mathcal{N}_i\}$, \mathbf{w}_h , and \mathbf{w}_e ,

which constitute the input to the control algorithm. The output of the control algorithm is \mathbf{u} , i.e., the control input to the actuators.

B. Communication Infrastructure

A network of robots is a group of robots whose processing units communicate through a communication infrastructure. The simplest way to model the overall communication state is to consider a graph $\mathcal{G} = \{\mathcal{S}, \mathcal{E}\}$, where the set of vertexes $\mathcal{S} = \{1, \dots, N\}$ represents the robots in the network, and $\mathcal{E} \subset \mathcal{S} \times \mathcal{S}$ is the set of edges for which $(i, j) \in \mathcal{E}$ if and only if $j \in \mathcal{N}_i$, where \mathcal{N}_i has been previously defined as the set of communication neighbors of the robot i .

A graph has an algebraic representation given by the adjacency and the incidence matrixes, denoted with \mathbf{A} and \mathbf{E} , respectively (see, e.g., [1], [2] for the formal definitions of these and all the algebraic graph concepts mentioned in this chapter). Another matrix that plays an important role in the control of networks of robots is the Laplacian matrix $\mathbf{L} = \mathbf{E}^T \mathbf{E} \in \mathbb{R}^{N \times N}$, which is always positive semidefinite, i.e., with all real and non-negative eigenvalues. A fundamental result in algebraic graph theory is that the multiplicity of the eigenvalue $\lambda_1 = 0$ of \mathbf{L} is equal to number of connected components of \mathcal{G} [3]. For this reason, the second smallest eigenvalue of \mathbf{L} , typically denoted with λ_2 , is called algebraic connectivity, and $\lambda_2 > 0$ if and only if the graph is connected. Those definitions extend seamlessly to the case of weighted graphs, i.e., graphs in which a weight number is associated to each edge, representing, e.g., the quality of the communication. Algebraic graph theory plays a fundamental role in the control of networked robots, see, e.g., [4] for an introduction to this vast topic.

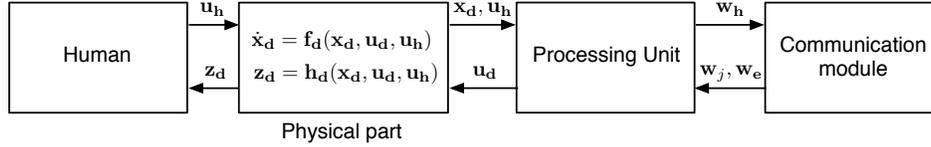


Fig. 2: High-level model of the human-robot interface.

C. Human-robot Interface

A *human-robot interface* is an input-output device that allows a human operator to retrieve/send information from/to one or more robots at the same time. The interface is constituted by a physical part, which is able to record the human actions and to provide a sensorial feedback to the human, a processing unit, and a communication module. Examples of interfaces are joysticks, control pads, button pads, displays, movement recognition units, and haptic interfaces, just to mention a few. We refer the reader to Figure 2 for a high-level model of a human-robot interface robot interacting with the human and communicating with the robots.

The *physical part* of the interface is implicitly modeled by a differential equation

$$\dot{\mathbf{x}}_d = \mathbf{f}_d(\mathbf{x}_d, \mathbf{u}_d, \mathbf{u}_h) \quad (4)$$

where $\mathbf{x}_d \in \mathbb{R}^{n_{x_d}}$, is the *state of the interface*, $\mathbf{u}_d \in \mathbb{R}^{n_{u_d}}$ is the *control input of the interface* (a signal that can be changed arbitrarily by the processing unit), and $\mathbf{u}_h \in \mathbb{R}^{n_{u_h}}$ is the *external input from the human operator* (a signal that is out of control of the interface and represents the human input to the system). We do not include inaccuracies and disturbances in the interface model since human-robot interfaces are typically well-calibrated instruments that operate in a structured environment. For the same reason we assume that the internal state of the interface \mathbf{x}_d is fully measurable.

The *communication module* feeds the interface with signals coming from a set of robots denoted with $\mathcal{N}_l \subseteq \{1, \dots, N\}$ and called *interface neighbors*. We denote the signal coming from the robot $l \in \mathcal{N}_d$ with $\mathbf{w}_{d_l} \in \mathbb{R}^{n_{w_{d_l}}}$. As in the previous case, additional signals coming from other sources (like, e.g., a smart environment) are denoted with $\mathbf{w}_e \in \mathbb{R}^{n_{w_e}}$. Finally, the communication module is also in charge of sending the signal \mathbf{w}_h to the robots in \mathcal{N}_d .

The *processing unit* of the interface has two roles. The first role is to compute \mathbf{w}_h on the basis of \mathbf{x}_d so that the human can influence the motion control of the robots. The second role is to provide a *feedback to the human operator* in the form of, e.g., an image, a change of color, a beep sound, a force provided back to the operator in a haptic interface, and so on. Generically speaking, any kind of feedback can be modeled by a static function

$$\mathbf{z}_d = \mathbf{h}_d(\mathbf{x}_d, \mathbf{u}_d, \mathbf{u}_h). \quad (5)$$

The input \mathbf{u}_d is computed with the purpose of letting \mathbf{z}_d be informative of the communicated signals $\{\mathbf{w}_j | j \in \mathcal{N}_l\}$, \mathbf{w}_h , and \mathbf{w}_e .

III. A TAXONOMY OF COLLABORATIVE HUMAN-ROBOT CONTROL

In this section we present a taxonomy¹ for the situation in which a human collaborates in the motion control of one or multiple mobile robots. We shall refer when needed to the terminology introduced in Section II. A particular emphasis will be given to the case of aerial robots, even though many results and considerations hold for any kind of mobile robot.

A. Physical Domain of the Robots

First of all, the *collaborative human-robot control* can be divided in several categories, corresponding to the physical domain of the robotic system, i.e., terrestrial (ground), aerial, space, marine, and underwater, just to mention the main ones. In the following we provide a quick review on the models used for the first two domains.

The models of ground robots stop typically at the kinematic level. An example is to consider $\mathbf{x} = (\mathbf{p}^T \ \boldsymbol{\psi}^T)^T \in \text{SE}(2)$ where \mathbf{p}^T and $\boldsymbol{\psi}$ are the position and orientation of the mobile robot, respectively. The simplest model can be represented as $\dot{\mathbf{x}} = \mathbf{u}$ if the robot is omnidirectional and holonomic or as $\dot{\mathbf{x}} = \mathbf{G}(\mathbf{x})\mathbf{u}$ with $\text{rank}(\mathbf{G}) < 3$ if the platform is underactuated and non-holonomic.

Aerial robots cannot be modeled just kinematically because the dynamic effects are non-negligible, due mainly to: 1) the larger speed of aerial robots when compared to ground robots, and 2) the impossibility to aerodynamically generate input forces that are as strong as the one generated using the motor-wheel actuators available in the ground robot case. Furthermore, in order to increase the energy efficiency, the mechanical simplicity and robustness, and the lightness of the platform, a low number of actuators are used, leading to underactuated robots. The most used aerial robots nowadays are multi-rotor platforms, such as, e.g., the quadrotor configuration [5]. In this case the robot state is the one of a rigid body floating in space $\mathbf{x} = ((\mathbf{p}, \mathbf{R}), \mathbf{v}, \boldsymbol{\omega}) \in \text{SE}(3) \times \mathbb{R}^3 \times \mathbb{R}^3$, where \mathbf{p} , \mathbf{R} , \mathbf{v} , and $\boldsymbol{\omega}$ represent the position, attitude, velocity, and angular velocity of the robot, respectively. The dynamical model is then the

¹A taxonomy that is comprehensive of all the possible cases and shows all the most important works in collaborative human-robot control is clearly out of the scope of this chapter, which does not claim to be a complete survey of this huge topic.

following

$$\dot{\mathbf{p}} = \mathbf{v} \quad (6)$$

$$\dot{\mathbf{v}} = \mathbf{f}_1(\mathbf{x}) + \mathbf{G}_1(\mathbf{x})\mathbf{u} \quad (7)$$

$$\dot{\mathbf{R}} = \mathbf{R}\boldsymbol{\omega} \quad (8)$$

$$\dot{\boldsymbol{\omega}} = \mathbf{f}_2(\mathbf{x}) + \mathbf{G}_2(\mathbf{x})\mathbf{u}. \quad (9)$$

In most of the cases, e.g., for coplanar multirotors, the attitude dynamics (the last two equations) is fully actuated (i.e., $\text{rank}(\mathbf{G}_2) = 3$), while the position dynamics (the first two equations) is under-actuated (typically $\text{rank}(\mathbf{G}_1) = 1$). Furthermore there is a cascaded structure in which \mathbf{f}_1 , \mathbf{G}_1 , \mathbf{f}_2 , and \mathbf{G}_2 depend only on \mathbf{R} and $\boldsymbol{\omega}$.

The increased range applications enabled by the use of aerial robots with respect to the exclusive use of ground robots, together with the larger complexity of aerial robots platforms made the design of collaborative human-aerial-robot control a particularly interest research domain. In this chapter we will therefore focus especially on the aerial robot case. However the proposed taxonomy and the large majority of presented methods apply for all the other domains as well.

B. Degree of Autonomy from the Human Operator

The *collaborative human-robot control* can be then roughly divided in three categories, corresponding to the degree of autonomy of the robotic system. This kind of classification, recalled in Table I, is similar to the one used in the teleoperation literature, see e.g., [6].

The separation between the three categories cannot be sharp. Typically, real situations show intermediate aspects between the three categories. In this chapter we will present works that belong mainly to shared control category, with some supervisory control aspects as well.

1) *Direct Control*: *Direct control* refers to the case in which the robot motion is completely (i.e., in all its DoFs) decided by the human operator. The role of the robot is only to reproduce the human operator motion with as much fidelity as possible. In this case the human-robot interface has the same number of DoFs of the robot ($n_x = n_{x_d}$), $\mathbf{w}_h = \mathbf{x}_d$, and the goal of the robot control \mathbf{u} is to have

$$J = \|\mathbf{x} - \mathbf{w}_h\| < \varepsilon \quad (10)$$

with ε as small as possible.

2) *Supervisory control*: *Supervisory control* refers to the case in which the robot motion is mainly controlled by autonomous decisions of the robot, while the human operator is in charge of providing only high-level directives to be fulfilled. In this also case the human-robot interface has typically a much lower number of DoFs of the robot ($n_x > n_{x_d}$), and the goal of the robot control \mathbf{u} is to minimize

$$J = \|\mathbf{h}(\mathbf{x}(t^*), \mathbf{x}_e(t^*)) - \mathbf{w}_h\| \quad (11)$$

where in this case $\mathbf{h}(\mathbf{x}, \mathbf{x}_e(t^*))$ is a projection map for both the robot and environment state and t^* are some particular time instants in which the sub-task should be achieved.

3) *Shared Control*: *Shared control* refers to the case in which the robot motion is determined by both the human operator and robot decisions in a mostly balanced fashion. In this case typically the human-robot interface has a lower number of DoFs of the robot ($n_x > n_{x_d}$), and the goal of the robot control \mathbf{u} is to minimize

$$J = \|\mathbf{h}(\mathbf{x}) - \mathbf{w}_h\| \quad (12)$$

where $\mathbf{h}(\mathbf{x})$ is a map that projects \mathbf{x} on the lower-dimensional space controlled by the human operator.

a) *Time Horizon in the Operator Reference*: Another important aspect in the collaborative control schemes that we are analyzing is the length of the time horizon associated to the reference signal (e.g., desired position or velocity) given by the operator to the robot. In the direct control case the length of time-horizon is intrinsically zero since the operator reference is instantaneous and refers to the ‘now’. On the contrary in supervisory control schemes the time-horizon is typically very large and the reference command pertains to some time instant in the relative long-term future, as explained before in this chapter.

In the shared control scenario the presence of intermediate cases is possible. However, in the literature, the majority of the shared control works considers that the human operator is in charge of guiding the aerial robot during the task by specifying the current reference position or velocity, as e.g., in [7], [8], [9]. This persistent commitment can result rather demanding for the human operator. Furthermore instantaneous and persistent collaboration may be unnecessary in some parts of the task execution, such as in all the applications in which the robot has to follow a predefined path and the purpose of the operator is only to provide sporadic modification to the planned path in response to unpredicted changes of the external situation.

In the work presented in [10] (see Figure 3 for an illustration of this scheme) this consideration is taken into account and the collaboration is shifted directly at the planning level by letting the human operator control the planned path for a given future (and non-negligible) time horizon. First, the operator is in charge of modifying online the shape of a planned path with a haptic interface (e.g., by changing the location of some control points). Secondly the robot autonomously correct the modified path in order to meet additional requirements such as collision avoidance, dynamic limits etc. Finally, consistently with the spirit of feedback-force schemes, the haptic cue is computed based on the mismatch between the path modification requests asked by the operator and the autonomous modifications of the robot using an impedance-like algorithm. In our formalism, this kind of paradigm can be summarized by the following equations:

$$J = \|\mathbf{h}(\mathbf{x}_{[t,t+T]}) - \mathbf{x}_d\| \quad (13)$$

$$\mathbf{u}_d = \mathbf{K}(\mathbf{h}(\bar{\mathbf{x}}_{[t,t+T]}) - \mathbf{x}_d) + \mathbf{f}(\mathbf{x}_d), \quad (14)$$

where $\mathbf{x}_{[t,t+T]}$ represents the future state of the robot in the time horizon $T > 0$, and $\bar{\mathbf{x}}_{[t,t+T]}$ is state re-planned by the robot.

TABLE I: Degrees of autonomy in the human-robot collaborative control

Non-robotic systems	Robotic systems		
	Collaborative human-robot control		Fully autonomous
Fully human-operated	Direct	Shared	

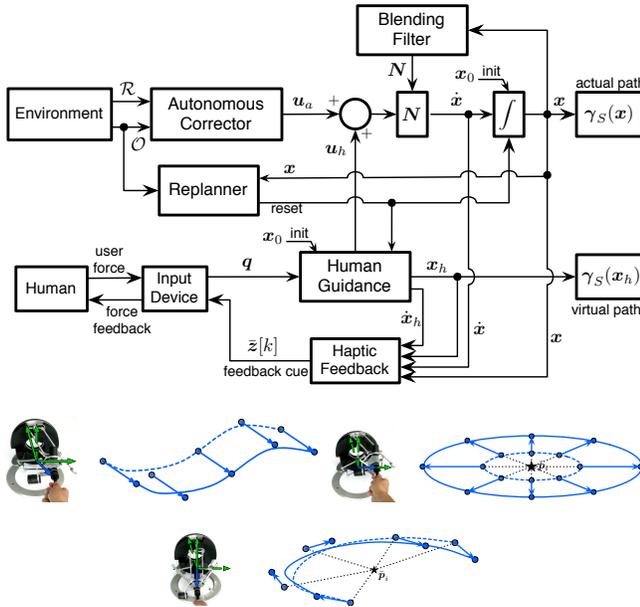


Fig. 3: Top: block diagram of a feedback-force human-robot collaboration scheme with relatively long time horizon in the operator reference.

Bottom: Examples of canonical path transformations. Green arrows represent the DoFs. Depending on the transformation the device motion is artificially restricted (continuous green arrows): 2 DoFs for translation, 1 DoFs for scaling, 1 DoFs for rotation. Blue arrows represent the commands and corresponding motion of the control points.

An interesting future direction in this sense would be to study task-dependent automatic adaptation of the length of the time-horizon in the operator reference.

4) *Outside Collaborative Human-robot Control*: Outside the two extremes of collaborative control there are two cases which do not involve collaboration, see Table I.

A robot is *fully autonomous* if the human operator has no influence on it, i.e., the signal \mathbf{w}_h is empty.

The antipodal case is when the human is in charge of steering all the DoFs by means of low-level actions, like while driving a (non-autonomous) car or operating a mechanical tool. In this case the machine is not a robotic system, because it lacks of any relevant autonomous aspect. The machine is said *fully human-operated*. In this case the human acts directly on \mathbf{u} .

C. Force Interaction with the Operator

Another distinction can be made depending on the information value given to the *mechanical exchange* between the human operator and the interface.

A collaboration scheme is *forward-force* if the force exerted by the human operator is informative for the collaborative control. In other words, in a forward-force collaboration, the human input \mathbf{u}_h includes a measure (or an indirect estimation) of the force exerted by the human operator on the human-robot interface and this measure influences \mathbf{w}_h as well.

A collaboration scheme is *feedback-force* (or *bilateral*) if the human-robot interface exerts, towards the human operator, a force that conveys some information related to the collaborative control. In other words, in a feedback-force collaboration the feedback to the human operator \mathbf{z}_d includes a force exerted by the interface toward the human operator. An interface that is not feedback-force (bilateral) is said *unilateral*.

Notice that:

- in this terminology, ‘unilateral’ means that there is no force feedback. Other kind of feedback signals (e.g., visual) may be still present in a unilateral scheme;
- a feedback-force scheme does not necessarily imply that the scheme is also forward-force and, vice versa, a forward-force scheme could be unilateral;
- the previous definitions can be extended by replacing force with mechanical quantities related to forces and, more in general, mechanical power such as, e.g., moments, stiffness/compliance, and friction.

Forward-force schemes include the so-called ‘force-position’ or admittance-based schemes, in which the force provided by the human operator \mathbf{u}_h is recorded by a force sensor or estimated by an observer on the human interface and it is used to generate online a reference position and velocity that the robot tracks using a local position control loop. In our formalism this kind of scheme can be represented by

$$\dot{\mathbf{x}}_{\text{ref}} = \mathbf{f}(\mathbf{x}_{\text{ref}}, \mathbf{u}_h) \quad (15)$$

$$J = \|\mathbf{h}(\mathbf{x}) - \mathbf{x}_{\text{ref}}\|. \quad (16)$$

This kind of approach has been used e.g., in [7] where the authors propose an admittance control modality for controlling an aerial vehicle. The operator applies a force to a haptic interface and the interface responds with a corresponding displacement, at the same time the force applied by the operator is used to generate a reference for the vehicle controller.

The simplest feedback-force schemes are the so-called ‘position-force’ or impedance-based schemes. In these schemes the configuration in which a haptic device is set by the operator is used a reference position or velocity for the robot. The force feedback is then proportional to the mismatch between the actual position/velocity and the reference. In our formalism this kind of scheme can be

represented by

$$J = \|\mathbf{h}(\mathbf{x}) - \mathbf{x}_d\| \quad (17)$$

$$\mathbf{u}_d = \mathbf{K}(\mathbf{h}(\mathbf{x}) - \mathbf{x}_d) + \mathbf{f}(\mathbf{x}_d), \quad (18)$$

where \mathbf{K} and $\mathbf{f}(\mathbf{x}_d)$ are a gain matrix and a stabilizing term for the device, respectively.

A seminal work in this field is [11], where a force feedback scheme based on virtual viscoelastic couplings is designed for controlling a ground mobile robot in an obstacle populated environment. Extension to the multiple ground-robot case has been considered, e.g., in [12]. Finally many applications and extensions of this concept to the aerial robot case can be found in the very recent literature, see, e.g., [13], [14], [15], [16], [8].

More advanced feedback force schemes include in the feedback the measurement of the force exerted by the robot on the environment or vice versa. In [17] the authors propose a scheme that is both forward-force and feedback-force to control an aerial robot. The forward scheme is similar to an admittance-like one, while the feedback force is used to display obstacles using the concept of dynamic kinesthetic boundary. In [18] a variable force-feedback gain is instead proposed.

Researcher efforts have also been directed toward the critical comparison between different schemes. In [19] a theoretical and experimental comparison between the admittance- and impedance-like schemes is proposed both from the perceptual and performance point of view. In [20] the authors compare two different haptic cueing, namely the aforementioned reference mismatch versus the obstacle force cueing.

The main advantage of forward-force schemes is the availability of an additional intuitive information channel for the human operator in the forward channel. The main disadvantage of forward-force is the necessity to measure the human force, which is usually very noisy and also difficult to give a unique interpretation among the different human operators.

The main advantages of feedback-force schemes are:

- the additional channel for providing information to the operator, which hopefully results in a more immersive experience;
- the fact that haptic feedback may result more immediate to interpret than visual feedback due to the longer cognitive pipeline related to the latter;
- the fact that haptic feedback requires less bandwidth than vision (e.g., to feedback the distance from an obstacle), which in turns generates less delay than vision in long-distance internet based communication, see, e.g., [21].

The main disadvantages of feedback-force are:

- the fact that the force applied to the interface influences back its the motion in a way that might result involuntarily for the operator;
- the increased difficult to ensure overall stability;
- the sensibility to delays;



Fig. 4: Experiments of intercontinental (Korean-German) feedback-force collaborative human-robot control. Top; scenario presented in [21]. Bottom: demo at the IEEE International Conference on Systems Man and Cybernetics 2012, in Seoul, South Korea.

- the need to take into account ergonomics issues, which may increase operator fatigue.

Stability issues in the bilateral human-collaborative control of mobile robots have been addressed in several ways, many of which related to passivity based control such as, e.g., the passivity observer/passivity controller (PO/PC) approach [22] the passive-set-position-modulation (PSPM) approach [23], and the two-layer approach [24].

D. Near-operation vs. Teleoperation

A human-robot collaborative control is a *near-operation* if the human operator perceives the scene related to the control task by direct sensing, e.g., by line-of-sight, sense of touch, etc. Conversely, the human-robot collaborative control is a *teleoperation* when the perception is made through indirect sensing, e.g., tele-vision, haptic interfaces, etc.

A teleoperation is *delayed* when the delays of the communication are non-negligible (due to, e.g., long distances or long processing times). As it is well known, the presence of delays in the teleoperation may have a dramatic influence on the stability of feedback-force schemes if not properly addressed, see, e.g., [6] and reference therein.

Large delays (usually greater than 0.15 s) between the operator and the robots are unavoidable in intercontinental collaborative control settings. In addition to stability, those delays generate also practical problems in the quality of video streaming, the safety and the ability to maneuver the robot. In fact, in long-distances communication, the video transmission has usually a larger delay than the reception of state of the remote robots because of the larger size of the packets of the video streaming.

Examples of intercontinental shared control of aerial robots are still very few at date. In [21] the authors

TABLE II: Amount of physical interaction of the robot(s) with the environment

Amount of physical interaction of the robot with the environment		
With contact	Contact-free	Negligible
The external environment constrains the DoFs of the robot	The forces produced by the external environment do not constrain the DoFs of the robot	The disturbing/constraining external forces are negligible

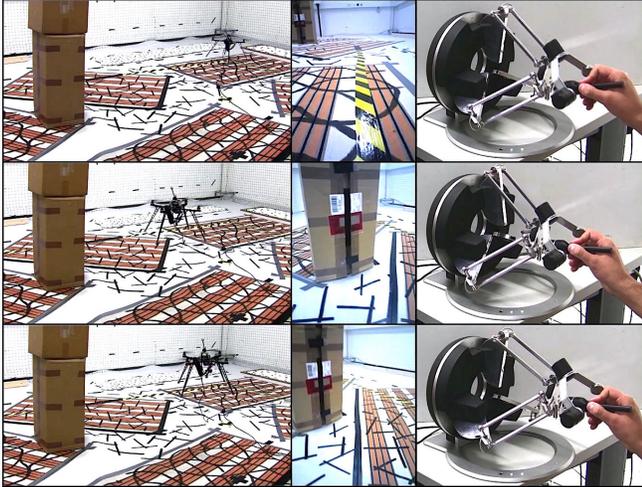


Fig. 7: Experimental validation of a feedback-force collaboration scheme that uses onboard only sensors, namely an RGB-D camera and an IMU [9].

between two different classes of approaches: the approaches that use external sensorial infrastructures and the approaches that make use of onboard only sensorial equipment. The large majority of works in collaborative control of aerial robots belong to the first category. Motion capture systems, global positioning systems (GPS), and wireless based localization are some example of the infrastructures used in these works [14], [30], [31], [8], [32].

Some recent efforts have been directed toward the second kind of approach, which presents clearly more challenges, especially in the aerial robotics case. The work in [33], where a bilateral teleoperation scheme for aerial robots is presented, represents a first step in the direction of the second class of approaches. In this work the state of the robot is retrieved using a motion capture system, however the obstacle detection is performed using a laser range finder which then feeds the obstacle avoidance algorithm with onboard data.

In the experiments presented in [34] a human operator controls a group of aerial robots that use onboard cameras to measure the relative angles between themselves while the velocity is still estimated using an external motion capture system.

One of the first work addressing the problem of full-onboard sensorial equipment in the collaborative feedback-force control of aerial robots is presented in [9]. The human operates with velocity control (and with the feedback-force paradigm) the aerial robot in an unstructured environment, see Figure 7. The state of the robot is estimated using only the onboard IMU and a depth camera (RGB-D). Thanks

to the availability of the depth information the obstacle safety is ensured. During the collaboration the aerial robot conducts autonomously some extra-tasks that increase the ergonomics of the operation and its safety. The main of these tasks is a continuous pan scanning that temporarily enlarges the field of view of the robot exploiting the yaw DoF that is left free by the human operator collaboration. This movement is compensated in real time using an adaptive filter thus allowing the operator to experience a yaw-rate-free operation. The haptic feedback is based on the impedance paradigm where the actual velocity is estimated using a photometric error approach.

The development of human-collaborative control schemes that can cope with the use of onboard sensors only is crucial for the employment in the real world. However this aspect has been often overlooked by the recent literature, while it should probably deserve a higher attention.

IV. A TAXONOMY OF COLLABORATIVE HUMAN-MULTI-ROBOT CONTROL

The collaborative scheme may include just one robot (*single-robot* case) or several distinct robots (*multi-robot* case). The use a group of coordinating and cooperating robots represents an enabling technology for a large number of applications. As a matter of fact multi-robot systems can show an improved robustness with respect to single point system failures and the capacity of adaptation to environments that are both uncertain and dynamic. Multi-robot systems may present also economical advantages compared to monolithic complex robots due to the lower price of small size systems. Range of applications span from data retrieval and collection, distributed sensing on large-scale areas, deep space interferometry, and search and rescue missions. Among multi-robot systems aerial robots play an essential role for their ability to cover large distances due to their speed and large areas thanks to the presence of the third (altitude) dimension.

Thanks to the appealing features and the great potentials of multiple aerial robot systems, the recent years have seen a sharp increasing in the study of collaborative human-robot schemes for such kind of robotic systems. The goal of this section is to revise and classify some of these approaches from a multi-robot perspective. In [5] the authors provide an overview that summarizes generic collaborative scheme for the bilateral shared control of groups of aerial robots. The proposed approach is able to integrate three main components, i.e., the human operator assistance, the force feedback and the control of the group topological and metrical properties. Regarding the last component the work suggests to consider three main cases, the unconstrained-, the connected-, and the constant-topology cases. In this section

we aim at generalizing this classification taking into account additional aspects related to the collaborative human/multi-robot interaction.

A. Level of Centralization

A first classification when dealing with human collaborative schemes for multi-robot systems is about the level of centralization. Several definitions of decentralization has been given in the literature, which often overlap with the concept of a distributed algorithm. Here we adopt a simple definition that is the following: a scheme is decentralized (or distributed) if the amount of communication (packets exchanged) and computation (complexity) for unit of time, and the size of memory needed by each robot and by the human-robot interface, are constant when the total number of robots is increased. A scheme that is not decentralized is centralized. Centralized schemes are the one that need for example the communication graph \mathcal{G} to be complete, i.e., $(i, j) \in \mathcal{E} \forall i \neq j$. Centralized schemes are also the one assuming that the human-robot interface sends the message \mathbf{w}_h to all the robots in the team, i.e., $\mathcal{N}_i = N$.

In general, decentralized algorithms are more scalable, i.e., applicable to higher number of robots, but are less efficient than centralized algorithm in the case of a smaller number of robot and when the communication bandwidth and the computation capabilities of each robot allow centralized implementations.

B. Master-leader-followers Schemes

A possible approach to collaboratively control a group of robots is the *master-leader-followers scheme*. In this scheme all the robots implement any decentralized control strategy resorting to local communication in order to carry on some task while the human operator (the master) communicates with only one robot of the group at time (the leader). All the non-leader robots are called the followers. For example the robotic team task could be to monitor a given area while keeping a certain formation, and the master, that is supervising the overall task providing, e.g., velocity references, can be in communication only with one robot at time due to long distance bandwidth limitations. This scenario is abstractly depicted in Figure 8(left).

Several challenging problems can arise even from this fairly basic situation when collaborative human-robot control is needed. A first example is the difficulty of maintaining the stability of the feedback-force interconnection between the human operator and such multi-robot system, especially in the case in which the multi-robot team interaction topology can arbitrarily switch even independently of the robot state. In fact, in [30] it is shown that this kind of switching interaction can generate a non-passive and potentially unstable behaviors. The authors then present a passivity-based approach to guarantee a stable behavior of the leader and the followers regardless of the autonomous motion, the switching topology and the interaction with the environment. At the same time, making the multi-robot system passive turns instrumental for the feedback-force collaborative scheme

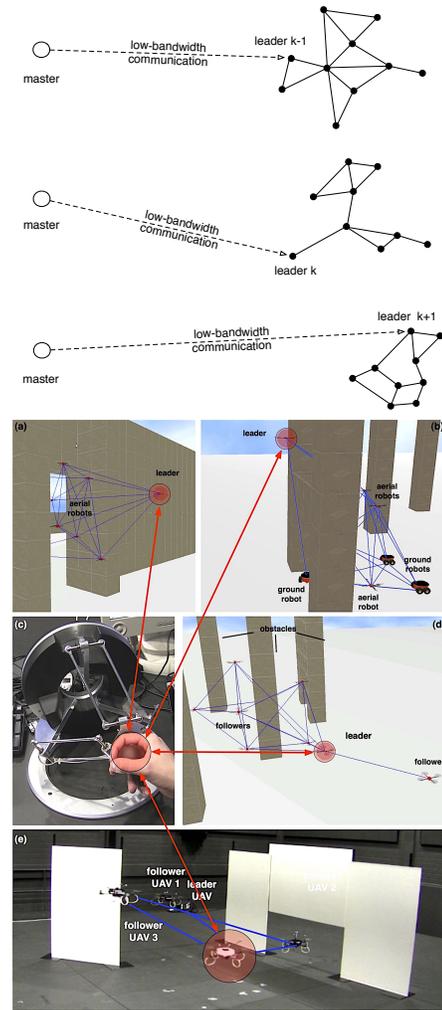


Fig. 8: Left: abstraction of master-leader-followers scheme. The human operator (master agent) can communicate only with one robot at the time (the leader) using a low channel bandwidth. The leader robot and the followers communicated through a time-varying distributed communication topology. Right: a human operator collaborates with a group of robots using as feedback-force scheme. Passivity of the heterogeneous team of robots is guaranteed despite the switching nature of the communication [30].

with the human operator (the master). Experiments using this approach are show in Figure 8(right).

Another challenge arising in this context is called the *online leader selection* problem, i.e., the ability of the system to choose online the best leader that the master has to communicate with. This problem is addressed, e.g., in [35], [36] for what concerns the maximization of the effectiveness of the velocity reference provided by the human operator. In this work the authors show that this effectiveness is upper-bounded by an index that depends on the current state of the robots and by a graph theoretical index, namely the algebraic connectivity of a special leader-dependent digraph.

C. Formation-orthogonal Control Schemes

Another approach to collaboratively control a group of robots is the *formation-orthogonal control* scheme. In this scheme the robots autonomously stabilize the relative geometry of the formation using relative or absolute measurements, while the human operator sends references to steer the remaining DoFs of the multi-robot system.

In [27], [12] the authors propose a method to bilaterally teleoperate a group robots such as, e.g., a group of ground mobile manipulators grasping an object. The main idea of the method relies on the concept of passive decomposition, with which it is possible to decompose the multi-robot dynamics in two independent systems while preserving passivity from an energetic point of view. The locked system abstracts the overall team motion and is controlled by the human operator using a feedback-force paradigm. The shape system defines instead the cooperative grasping aspect and is autonomously controlled by the team of robots. This paradigm allows the human to indirectly control the motion of the grasped object without influencing the reliability of the grasping.

Regarding the aerial robot case, in [31] the authors propose a feedback-force collaboration scheme in which the human operator teleoperates the motion of the multiple aerial robots that act as a virtual deformable object. The scheme is based on three layers: the low-level robot control, the online velocity reference generator, and the bilateral teleoperation layer. The low-level robot control is used in order to abstract from the particular kind of dynamics of the robot. The velocity reference generator mixes together the velocity reference provided by the operator, the obstacle avoidance action, and the distance preservation term. The last two terms are based on an artificial potential approach. The haptic cue provided to the operator is proportional to the average of the velocity reference mismatch in a way that is similar to an impedance-like approach, but extended to the whole multi-robot system considered as a virtual large deformable object. In order to implement this formation control scheme the position measurements of each robot (e.g., from GPS) are needed.

An alternative (especially from the sensing point of view) formation-orthogonal control scheme is presented [34], see Figure 9. This case differs from [31] for three main aspects. The first is that it uses only measurements of the relative angles between the robots (that can be, e.g., retrieved from onboard cameras). The second is that the formation control approach used is almost globally convergent and it is not prone to local minima like the artificial potential schemes typically are. The third is that the human operator velocity reference acts on the tangent bundle of the manifold of configurations that keep the relative angles constant, which includes collective rotations, translations, and dilations. In this way the formation control specifications and the human control result always orthogonal and do not interfere with each others thus establishing a clear separation between the fully autonomous and the human-operated domains of intervention.

D. Group-property Preservation Schemes

Formation-orthogonal control schemes may excessively limit the relative mobility between the robots in the group by, e.g., blocking the relative distances and angles to some fixed or overly constrained values. On the other side, for some tasks it is enough to preserve some high-level structural properties of the group rather than determining the exact shape of it. We refer to such approaches as *group-property preservation schemes*.

A first example of high-level structural property of a group of robots is the connectivity of its topology, intended either as the communication network or the sensing graph. Connectivity is a very important property since it ensures that the data flow between the different robots cannot be broken and therefore the information can be successfully distributed.

In [1] the authors present a decentralized method that maintains group the connectivity in a flexible way, i.e., allowing the topology to change over time as long as connectivity is preserved, see Figure 10. Connectivity preservation is ensured by keeping the algebraic connectivity λ_2 (see Section II-B) positive during all the robot maneuvers. The algebraic connectivity concept is then extended to take into account complex robot-to-robot interaction going beyond simple max-distance models, which brings to the definition of the generalized connectivity eigenvalue. This is obtained by introducing a state-dependent adjacency matrix $\mathbf{A}(\mathbf{x}_1, \dots, \mathbf{x}_N)$ and consequently, a state-dependent Laplacian $\mathbf{L}(\mathbf{x}_1, \dots, \mathbf{x}_N)$. The resulting generalized connectivity is also able to embed mild formation control constrains and obstacle avoidance if needed. Exogenous control actions coming from human operators or from a distributed target visiting algorithm, like the one presented in [37], can be also included. Using a feedback-force collaborative scheme one or more human operators can interact with the group of robots and immersively feel, through haptics, the connectivity force generated by the group.

Connectivity alone might be not enough to achieve certain tasks in which the robots can rely on relative sensing only. In these cases it is more appropriate to consider the concept of rigidity instead, which defines the property of being able to instantaneously reconstruct the group shape using local relative measurements, such as relative distances or relative angles. The rigidity concept has been originally introduced in the structure theory in order to characterize the notion of flexibility and stiffness of rigid-body structures.

The main algebraic object of what is called infinitesimal rigidity [2] is the so called rigidity matrix $\mathbf{R}(\mathcal{G}, \mathbf{p}_1, \dots, \mathbf{p}_N)$ which is defined as

$$\mathbf{R}(\mathcal{G}, \mathbf{p}_1, \dots, \mathbf{p}_N) = [\mathbf{E}_I(\mathcal{G}_1)^T \cdots \mathbf{E}_I(\mathcal{G}_N)^T] (\mathbf{I}_N \otimes [\mathbf{p}_1^T \cdots \mathbf{p}_1^T]^T)$$

where $\mathbf{E}_I(\mathcal{G}_i)$ is the local incidence matrix relative to the i -th robot, \mathbf{I}_N is the $N \times N$ identity matrix, and \otimes denotes the Kronecker product between matrices.

In the context of multi-robot systems, the authors of [2] develop a theoretical machinery to express the degree of rigidity using a single non-negative number, namely the

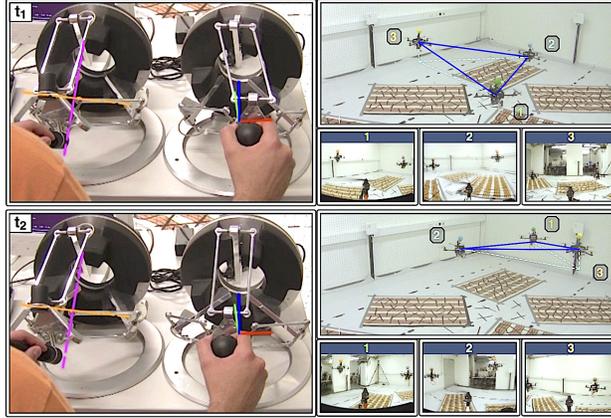
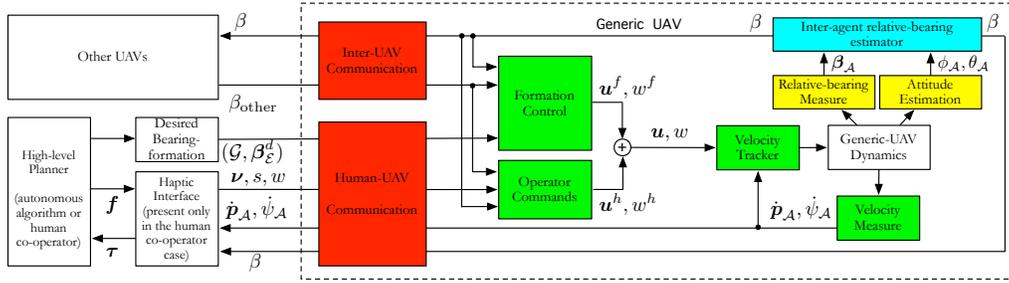


Fig. 9: Top: block diagram of a formation-orthogonal collaboration scheme that uses relative bearing (angle) measurements [34].

Bottom: implementation with aerial robots using onboard cameras to retrieve the bearing measurements.

rigidity eigenvalue, defined as the smallest non-structurally-zero eigenvalue of the symmetric rigidity matrix

$$\mathcal{R} = \left(\mathbf{W}(\mathbf{p}_1, \dots, \mathbf{p}_N) \mathbf{R}(\mathcal{G}, \mathbf{p}_1, \dots, \mathbf{p}_N) \right)^T \left(\mathbf{W}(\mathbf{p}_1, \dots, \mathbf{p}_N) \mathbf{R}(\mathcal{G}, \mathbf{p}_1, \dots, \mathbf{p}_N) \right)$$

where \mathbf{W} is the diagonal matrix of the state-dependent weights defined on the edges of \mathcal{E} . The authors in [2] present a distributed algorithm that ensures the preservation of the rigidity resorting to local relative distance measurements only. Experiments are shown in which multiple human operators can interact with the group of robots providing velocity references while the group of aerial robots preserves the required degree of rigidity in an autonomous way. As in the connectivity case, haptic cues can be used to perceive the group rigidity using the feedback-force scheme.

Another advanced way of establishing a collaboration between human and the robotics team in the group-property preservation schemes is to let the human finely control the index that defines the group properties as, e.g., the connectivity and the rigidity eigenvalues, using one of the DoFs of the interface. A work that explores this idea in a feedback-force fashion for the connectivity index is presented in [38].

E. Physical Interaction with Contact

We have already shown examples of coordination of ground robots physical interaction with contact, such as, e.g., [27], [12]. Many other works are present in the literature

for the ground mobile robot case which are not mentioned here. On the other side, human collaborative control of multiple aerial robots performing physical interaction with contact is a very young research field and not many works have been considering this scenario at date.

In [39] it is proposed a control framework to let a group of aerial robots grasp an object in a way that each robot uses an attached rigid tool to establish a single contact, see Figure 11. Each robot acts as a flying finger that collaborates with the others to establish a N-fingered hand. In this way the aerial robots realize a unique hand-like system that can grasp and transport an object. The whole system is operated by a human hand using a two-layer approach. First the operator hand is tracked with an RGB-D camera and some features are extracted and mapped to virtual attraction points. Secondly the aerial robots use an impedance force control in order to track the virtual attraction points with some compliance thus enabling grasping and transportation. The approach is validated in simulation only.

Another approach that solves a similar problem from the robot cooperative side but it lacks of the human collaborative part, is presented in [40]. In this work multiple aerial robots are connected to an object using spherical joints and are used as thrust generators to cooperative manipulate the object in a physical interaction with contact scenario. The method, which is validated with experiments using a team of quadrotors as aerial robots, represents a promising building block for a possible extension to the human collaborative

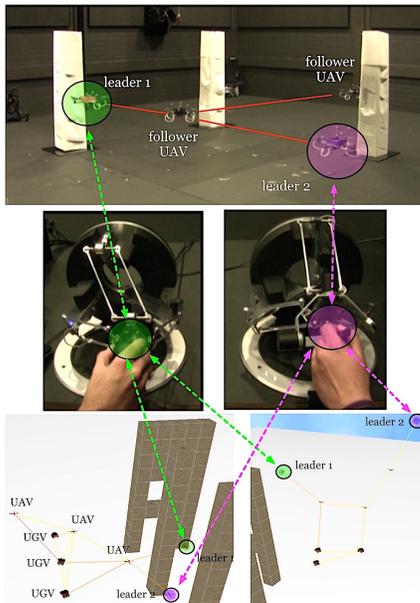


Fig. 10: Experiments and simulations involving two operators controlling groups of mobile robots in a generalized connectivity preservation scheme [1].

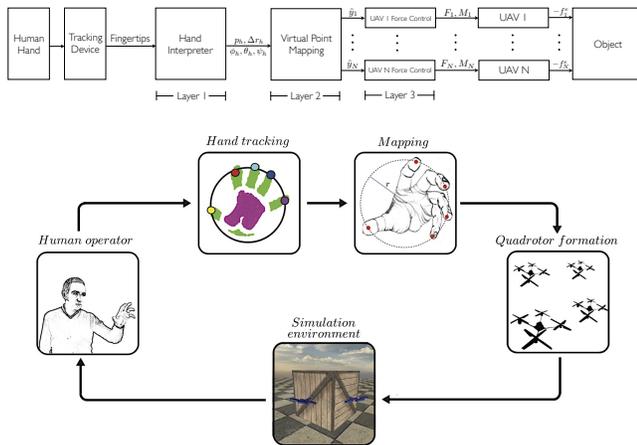


Fig. 11: Block diagrams of the flying hand collaboration concept. Each aerial robot acts as a single finger to grasp an object and the is teleoperated by a human hand through the use of a suitable abstraction layer [39].

case.

V. CONCLUSIONS

In this chapter we have shown and compared several different ways available in the literature to design the human collaborative control of the motion of mobile robots, with particular emphasis on the aerial robot case. We have introduced a simple yet descriptive model for the robots and the human interfaces and we have proposed a list of fundamental axes for a proper classification of the collaborative scheme, including but not limited to the degree of autonomy, the presence of interaction force with the human or with the environment, the kind multi-robot schemes and many others.

The common denominator of all the classification axes proposed in this chapter is the presence of a human operator in the control loop. In fact, fully autonomous control algorithms are not in general easily extendable in order to cope with the presence of a human operator and at the same time to take the best out of this collaboration. The main goal of the chapter has been to introduce the reader and provide a first-level analysis on the several ways to effectively include human operators in the control of both single and multiple aerial mobile robots. A particular emphasis has been set on the aerial robots case, which is at date not yet fully explored and understood, and is among the most challenging cases in robotics.

A lot of problems remain still unsolved in this field, among of which is worth to mention the possibility to perform effective bilateral teleoperation of aerial manipulators, the possibility of relying on onboard sensing in any environmental situation, the ability to cope with the large uncertainty in the perception and control of bilaterally teleoperated aerial robots thus enabling their use in the real world for helping humans in the industry and in their everyday life.

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