Force-based Cooperative Aerial Manipulation

Chiara Gabellieri[1], Marco Tognon[2], Lucia Pallottino[1], Antonio Franchi[3]

***Abstract*—The applications of aerial robotics have moved from visual inspection of the environment to physical interaction with it. One of the main applications of aerial physical interaction is object manipulation, which is of particular interest for delivery and construction. Concerning deliveries, aerial robots are independent of the traffic jam and may have a positive environmental impact compared to road transport. In construction, their large workspace can be beneficial as well. With a cooperative approach, payload limitations can be overcome, and regulation of the object full pose, especially important in assembly and construction applications, can be achieved. However, the communication needed for multi-robot coordination increases the system complexity and may undermine the performance. This work describes a cooperative method for manipulating cable-suspended objects with aerial robots without relying on direct communication. Instead, the sought coordination is achieved through force sensing.**

***Index Terms*—Aerial Manipulation, Force-based Coordination, Cooperative Manipulation**

I. INTRODUCTION

In the last decade, aerial robotics have been driven by opportunities for compliant and safe physical interactions. Nowadays, the spectrum of applications of these robots has been widening from the mere observation of the environment towards the physical interaction with it.

The targeted missions for aerial manipulators include construction [1] and load transportation[1]. Both sectors would benefit from the possibility of manipulating object at a considerable height. In this way, the work safety in construction applications might be improved. On the other hand, deliveries often rely on road transport [2], so that they are affected by the traffic jam in an unpredictable way and cannot be reliably scheduled. Instead, aerial manipulators are independent of traffic. According to a recent study published in Nature Communications [2], the use of aerial drones for deliveries would have a positive environmental impact, reducing greenhouse gas emissions.

In order to manipulate objects, aerial platforms have been endowed with different physical interaction tools, such as rigid tools, complex manipulators [3], and cables [4], which have received great attention for their simplicity and low weight.

Fig. 1. A cable-suspended object manipulated by multiple aerial robots.

Load manipulation often takes advantage of the *cooperation* between multiple robots to enhance the overall payload and thus lift heavy loads. Multi-robot manipulation also enables object full pose control, which is not possible with, e.g., just one underactuated vehicle. Full pose control can be of primary importance in assembly and construction.

However, explicit communication, required for the coordination of multiple robots, may represent an issue. Delays and packet corruption and losses can potentially undermine the performance and efficacy of these control laws. Furthermore, the hardware and software complexity of the system can be reduced by confining the explicit communication.

II. FORCE-BASED AERIAL CO-MANIPUALTION

A. General Idea

In this work, a method for communication-less cooperative manipulation with aerial robots, introduced in [5], [6], and [7], is described. The objective is regulating the pose of a manipulated object. The object is manipulated through cables, each cable is attached to an Unmanned Aerial Vehicle (UAV). A schematic representation of the system is reported in Fig. 1.

The proposed method exploits a leader-follower scheme and does not rely on explicit communication among the agents. Instead, a sort of implicit *physical communication* takes place among the robots through the load and the cables. Thanks to this form of implicit communication, the robots retrieve information to coordinate themselves in a decentralized fashion. All robots are controlled via admittance control laws, and the leader robot is the only one attracted to a reference trajectory; the apparent stiffness of the follower robots, instead, is set to

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[1] Research Center “E. Piaggio”, Department of Information Engineering, University of Pisa, Pisa, Italy chiara.gabellieri1@gmail.com and lucia.pallottino@unipi.it

[2] Autonomous Systems Lab, Department of Mechanical and Process Engineering, ETH Zurich, 8092 Zürich, Switzerland, mtognon@ethz.ch

[3] Robotics and Mechatronics department, Faculty of Electrical Engineering, Mathematics and Computer Science, University of Twente, 7500 AE Enschede, The Netherlands, a.franchi@utwente.nl

[1] https://www.cbsnews.com/news/amazon-unveils-futuristic-plan-delivery-by-drone

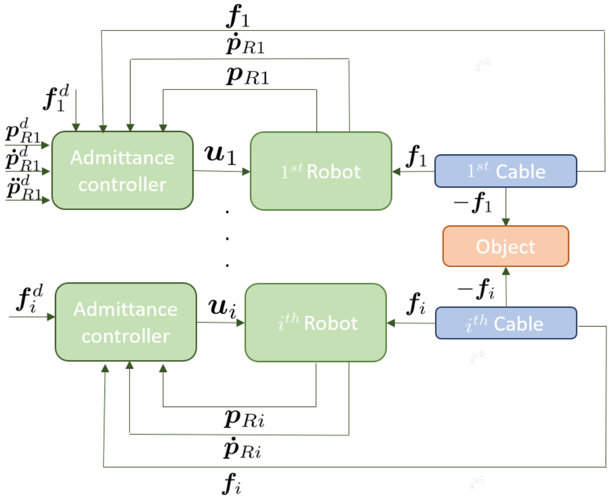

Fig. 2. Schematic representation of the controlled system. Cable force $\boldsymbol{f}_i$ acts on the i^{th} robot and enters its admittance controller, which takes also a reference force, $\boldsymbol{f}_i^d$, and the position and velocity of the i^{th} robot, $\boldsymbol{p}_{Ri}$ and $\dot{\boldsymbol{p}}_{Ri}$, as inputs. The control input of the robot is $\boldsymbol{u}_i$. The leader robot, robot 1, has also a reference trajectory, $\boldsymbol{p}_{R1}^d$, $\dot{\boldsymbol{p}}_{R1}^d$, and $\ddot{\boldsymbol{p}}_{R1}^d$.

zero. All the robots, however, have a reference external force and actively move in order to bring the cable force to that desired value. The reference forces are chosen such that the resulting wrench on the transported object is of equilibrium for a certain desired pose of the object. A schematic representation of the controlled system is in Fig. 2.

Intuitively, the leader robot moves to track a reference trajectory, and, in this way, it drags the common object. Consequently, the follower robots sense a change in their own cable force—for the control law implementation, the robots must measure or estimate the force in their own cable. Hence, they move in the direction of the force change in order to restore the force reference value. The resulting effect is that they follow the leader robot.

B. The Role of the Object Internal Force

When setting the robot reference forces, the most intuitive idea would seem to choose them just to compensate the weight and thus be able to lift the load. However, in [5], [6], and [7] we have shown that some additional component of the reference force, despite representing a source of energy consumption and stress on the object and the robots, is crucial for the convergence of the object pose to the desired equilibrium. The resulting additional force is referred to as the object *internal force*, and its effect is a stretching/compression of the object. Specifically, we have shown that

- reference forces that *stretch* the object make the desired object pose an asymptotically stable equilibrium;
- reference forces that *compress* the object make the desired object pose an unstable equilibrium;
- *zero* internal forces correspond to a continuum of equilibrium points, so that none of them can be asymptotically stable but only simply stable.

Simulating external disturbance torques on the object, we have shown that the internal force is beneficial for resisting external disturbances, too. Moreover, preliminary results suggest that stretching reference internal forces increase the system robustness in the presence of parametric uncertainties.

C. Extensions—Multiple Leader Robots and Ground Robots

The proposed method, with minor modifications regarding, e.g., gravity, can be applied also to omnidirectional *ground robots*, as proposed in [7]. The role of a reference stretching internal force on the object is analogous to the one described for the aerial case.

Moreover, it is possible to pick *multiple* leader robots; however, their reference trajectories must be coordinated. As a result, in the ground case *two* evenly distributed leader robots are enough, despite the value of the reference internal force, for convergence of the object pose and for increasing the robustness of the object orientation in the presence of external disturbances. The same happens in the aerial case with *three* evenly distributed leader robots.

III. CONCLUSIONS

This work described a method for enabling cooperative transportation of cable-suspended objects with aerial robots not explicitly communicating among them. This is done by controlling each robot via admittance controllers, assigning a reference trajectory to the leader robot, and setting to zero the apparent stiffness of the others. The robots follow reference forces by sensing/measuring the forces in their own cable. Setting reference forces that produce an internal stretch on the common object leads to asymptotically stable regulation of the object pose and is also beneficial for robustness to disturbances and parametric uncertainties. The method is applicable also to ground robots. The effect of multiple leader robots is discussed.

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