Introduction to the Special Issue on Aerial Manipulation

Fabio Ruggiero, Vincenzo Lippiello, and Anibal Ollero

I. Introduction

AERIAL manipulation is intended as grasping, positioning, assembling and disassembling of mechanical parts, measurement instruments and any other kind of objects, performed by a flying robot equipped with arms and grippers.

Aerial manipulators can be helpful in those industrial and service applications that are considered very dangerous for a human operator. For instance, think of tasks like the inspection of a bridge, the inspection and the fixing-up of high-voltage electric lines, the repairing of rotor blades and so on. These tasks are both very unsafe and expensive because they require the performance of professional climbers and/or specialists in the field. A drone with manipulation capabilities can instead assist the human operator in these jobs or, at least, in the most hazardous and critical situations. As a matter of fact, such devices can indeed operate in dangerous tasks like reaching the bottom of the deck of a bridge or the highest places of a plant or a building; they can avoid dangerous work at height; aerial platforms can increase the total number of inspections of a plant, monitoring the wear of the components. Without doubts, aerial manipulation will improve the quality of the job of many workers.

From a technical point of view, grasping an object during the flight with an aerial robot (equipped with only a gripper) poses several problems due to the very close proximity to the object, the under-actuation of the aerial vehicle, its unstable dynamics, the aerodynamic effects, and the dynamic effects given by the presence of the object. The bigger the carried payload, the more significant should be the capacity of the single employed aerial robot. However, the single gripper is not able to provide enough dexterity to perform useful manipulation tasks in the air. Mechanical structures mounted on the flying robot are then essential to perform more complex actions. Therefore, an aerial manipulator might be an efficient solution providing an aerial vehicle with the capability of performing dexterous manipulation tasks. Nevertheless, like the presence of a carried object creates effects in the dynamic model of the system, a mounted robot arm provides even more issues since its dynamics depends on the actual configuration state of the whole system. This Special Issue aims at collecting the latest results achieved by researchers working in mechatronics, sensing, motion planning and control within the aerial manipulation research field.

Nevertheless, a lot of work is still on the way. In general, energy and safety issues are still two main limitations. The lack of high accuracy is also relevant in many applications. A significant forthcoming challenge will be related to the power consumption and the current short-life of the batteries. Moreover, several countries have established regulations to limit the use of drones in open and crowded spaces for safety reasons. Finally, most current applications involving aerial manipulators are still settled in organized research laboratory environments. Only quite recently some aerial manipulators are being tested in realistic environments and will be tested soon in industries. Hence, such aerial devices should be able to work in real-world scenarios and applications, in which the weather conditions might be inclement and the equipment must be adequately verified (i.e., it must be explosion proof through ATEX or IECEx certifications).

II. Outline of the Special Issue

As sketched above, aerial manipulation is a broad topic and an ongoing expanding field. Ruggiero *et al.* wrote a related survey in [item 1) in the Appendix], collecting the results reached by the research community so far within the field of aerial manipulation, especially from the technological and control point of view. A brief literature review of general aerial robotics and space manipulation is carried out as well.

This Special Issue collects nine further letters tackling some of the fundamental challenges and opportunities in aerial manipulation. The following pattern can be recognized as an outline. Next subsection presents the works dealing with flying manipulation tasks through a single-arm aerial robot. Following, some solutions involving dual-arm aerial manipulation platforms are introduced. Finally, aerial manipulation solutions involving multiple flying robots are described.

A. Single-Arm Aerial Manipulation

Three letters in this Special Issue address new solutions to advance the current state of the art of flying manipulation tasks solvable with a single-arm aerial manipulator.

Kim *et al.* propose a stabilizing regulation controller in [item 2) in the Appendix] for a flying robot equipped with a (heavy) manipulator arm. The stability proof does not include any assumption, like a small angle attitude of the aerial vehicle or the coincidence between the first link of the arm and the center of mass of the flying robot. Limitation on the tracking case is any way discussed.

A novel method to cope with aerial manipulation problems is instead proposed by Tognon *et al.* in [item 3) in the Appendix]. Because trajectories generated by planning methods may have good theoretical properties, in practice, especially in the aerial manipulation field, the control methods applied for motion ex-

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ecution may have difficulties in tracking them. Therefore, they introduce the concept of a control-aware planner based on the paradigm of a tight coupling between the planner and the controller. The proposed sampling-based motion planner uses a controller composed of a second-order inverse kinematics algorithm and a dynamic tracker, as a local planner. Such a method predicts the behavior of the controller avoiding motions that bring to singularities or large tracking errors, and guarantee the correct execution of the maneuver.

Finally, inspired by the locomotion field, Delamare *et al.* address the problem of letting an aerial robot, equipped with a robot arm, exploiting its contact with the environment to enhance its motion possibilities. Therefore, the authors in [item 4) in the Appendix] consider the opportunity for the aerial manipulator to hook at some pivot points and reach a final anchored configuration while passing through a free-flight phase. They present a suitable dynamical model for both the hooked and free-flying stages, together with an optimization framework for generating optimal motion plans under constrained actuation.

B. Dual-arm Aerial Manipulation

Two letters in this Special Issue deal with problems related to the aerial manipulation with a single flying robot equipped with a dual-arm system. In particular, the design and the development of high-performance robotic arms for dual-arm aerial manipulators is addressed by Suarez *et al.* in [item 5) in the Appendix]. The letter shows how force/torque and virtual variable impedance control schemes can be implemented based on the deflection signal, estimated by a stereo vision system, of a compliant spring-lever transmission mechanism. The vision system also increases the position accuracy and allows the estimation and the control of the contact forces, without the need for additional sensors. Three new image-based visual-impedance control laws are instead proposed by Lippiello *et al.* in [item 6) in the Appendix], allowing physical interaction of a dual-arm aerial platform equipped with a camera and a force/torque sensor. Visual information is employed both to coordinate the camera motion in an eye-in-hand configuration with the assigned task executed by the other robot arm, and to define the elastic wrench component of the proposed hybrid impedance equations directly in the image plane.

C. Cooperative Aerial Manipulation

Four letters in this Special Issue finally cope with aerial manipulation tasks that can be solved by a team of flying robots.

In [item 7) in the Appendix], Loianno *et al.* describe the successful results achieved in cooperative localization, grasping, and transportation of magnetic objects in a challenging outdoor scenario like the Abu Dhabi desert. An autonomous team of aerial vehicles can localize and grasp ferrous objects from the ground autonomously. The final goal is the transportation of such objects to a final common destination while planning a safe and collision-free trajectory for each agent. Difficulties of the desert scenario include inconsistent wind, uneven terrain, and sandy conditions.

Six *et al.* develop the concept of cooperative aerial manipulation for object transporting in [item 8) in the Appendix] taking inspiration from a parallel manipulator. The letter introduces a novel idea of a flying platform composed of three aerial platforms linked by a rigid articulated passive architecture. Such a configuration offers the ability to control both the platform position and orientation in space. The study of the dynamic model shows decoupling properties exploited to design a robust cascaded controller adapted for this flying robot.

A framework integrating control, estimation of unknown payload, safety management, and obstacle avoidance for cooperative transportation in unknown environments using multiple aerial manipulators is carried out by Lee *et al.* in [item 9) in the Appendix]. Without using force/torque sensors, the proposed design is made up by an online estimator of the mass and the inertial properties of the unknown cooperative transported payload. An adaptive controller based on such estimate is developed in turn. Finally, dynamic movement primitives modify the trajectory in real time to avoid obstacles during the flight.

Finally, Tognon *et al.* tackle the cooperative manipulation of a cable-suspended load with two generic aerial robots in [item 10) in the Appendix], without the need of explicit communication between the agents. The proposed master-slave architecture exploits an admittance controller to coordinate the robots in a decentralized fashion, using the cable forces. The role of the internal force for the asymptotic stability of the beam position-and-attitude equilibria is deeply analyzed. As a result, contrarily from what it is typically done in the literature (i.e., zero internal force), it is advisable to choose a positive internal force to control both position and orientation of the beam.

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Appendix
Related Work

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Fabio Ruggiero was born in Naples, Italy, on December 16, 1983. He received the Ph.D. degree from the University of Naples, Naples, Italy, in 2010. Fabio Ruggiero held several postdoctoral positions from 2011 to December 2016. Starting from that month, he has been an Assistant Professor with the Department of Electrical Engineering and Information Technology, University of Naples. He has co-authored about 45 journal papers, book chapters, and conference papers. His research interests are focused on dexterous and dual-hand robotic manipulation, even by using UAVs with small robotic arms, dynamic nonprehensile manipulation, 3-D object preshaping, and reconstruction. He was the recipient of the 2015 I-RAS Young Author Best Paper Award.

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