Chapter 1
Introduction

1.1 Aerial Physical Interaction

One of the robotic fields in constant growth in the last decade is *aerial robotics*. According to [1], the definition of aerial robotics can be twofold: *(i) robotic flying machines*, putting the emphasis on the platform, or *(i) robotics that use flying machines*, putting the emphasis on the mission instead. In both cases, the main goal of aerial robotics is to study and conceive aerial systems that can perform work fully or partially autonomously. In the related literature, such robotic aerial platforms are often called *Unmanned Aerial Vehicles* (UAVs).

Although it is only recently that UAVs gained the interest of a very big and still increasing community, the study and design of such systems started already in the early 1900s. These vehicles were firstly used as prototypes to test new aircraft concepts before being produced and piloted by human pilots, decreasing the costs and the risks. The design of UAVs continued during the two World Wars for military purposes. However, the technology level was not enough to produce aerial robots able to autonomously navigate in a reliable way. It is only relatively recently, with the advent of lightweight and performing processors, accurate sensors and global navigation satellite systems, that aerial robots started to progressively gain better sensing and navigation capabilities. Although firstly employed in the military area, UAVs got a lot of interest from the civil area as well. Given the exponential appearance of new aerial vehicles and new applicative fields, the Economist compared the "drone boom" like the one happened to personal computers in the 1980s [2].

The motivation of the great popularity of UAVs mainly comes from the downscale of the size, weight, and cost of the sensing and computing technology. The latter made UAVs lighter, much more powerful and less expensive too. In turn, this allowed UAVs being accessible by a very wide community, both from the research and industrial areas. The low cost, the theoretically infinite workspace and the great versatility of these platforms allow employing them for several applications. In particular, they find their greatest use in dangerous and hazard environments, preventing

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humans from getting harmed. Some examples of application where UAVs are nowadays employed are agriculture, construction, security, rescue, response to disasters, entertainment, photography and movie making, archeology and geographic mapping, wildlife monitoring/poaching, and many others can be mentioned. Other near-future interesting applications, currently under study, are personal and goods transportation (e.g., Volocopter[1] and Amazon,[2] respectively).

Several types of aerial vehicles are available in the market:

(1) *Rotary wings UAVs*, like multirotors, small-scale helicopters, and ducted fan;
(2) *Convertible UAVs*, like tail sitter aircrafts, that combine cruising flight and Vertical Takeoff and Landing (VTOL) capabilities [3];
(3) *Flapping wings UAVs*, inspired by the flight of birds, bats, and insects;
(4) *Fixed wings UAVs*, very popular for their long flight time.

According to the particular application, one could choose the vehicle that better fits the sought task, finding the best trade-off between flight endurance and maneuverability.

Particular attention is given to VTOL vehicles thanks to their high maneuverability and the ability to hover in place and to take off and land from/on confined spaces, without the need of a runway or other devices. These facts make VTOL vehicles applicable also in indoor and cluttered environments such as forests, industrial plants, and urban environments. A brief review of these type of vehicles is given in Sect. 3.2. Beyond the mentioned nice features of VTOL UAVs, they suffer from a major drawback. Standard VTOL vehicles, like collinear multirotors, can produce a total thrust force only along one fixed direction with respect to the body frame (they can also be called *unidirectional-thrust aerial vehicles*). This makes them *underactuated*. It means that we cannot fully control the vehicle state. In particular, one cannot control the attitude independently from the position. Starting from a hovering configuration (horizontal attitude), in order to move toward a certain direction the vehicle has firstly to rotate such that the thrust generates a horizontal acceleration toward the desired direction. This underactuation introduces several challenges for the stabilization of the system and the tracking of the desired trajectory. It also implies that an external disturbance cannot be immediately rejected. The platform has firstly to tilt. For these reasons, several works have been done to design controllers of increasing complexity to improve the performance of such vehicles, e.g., in [4–7]. Additionally, many state observers have been conceived to close the control loop to autonomously fly in different conditions and with different sensory setups. For more details on control, localization and motion planning methods for the navigation of VTOL UAVs, we refer the reader to the main surveys and books in the literature [8–12]

One can notice that in all the application mentioned so far, the robot is used as a simple remote sensor. The vehicle gathers data, e.g., with a camera, without interacting with the environment. Although the use of UAVs for applications concerning only the sensing of the environment is already an interesting and challenging topic,

[1] http://www.volocopter.com.

[2] http://www.amazon.com/Amazon-Prime-Air/b?ie=UTF8&node=8037720011.

it is actually limited with respect to the real potentiality of these aerial robots. The paramount scope of robots is to perform physical work, namely to act and interact with the environment exchanging forces. *Aerial Physical Interaction* (APhI) would lead to new very interesting applications. Some examples are assistance robotics in industrial or domestic environments, assembly and construction, decommissioning, inspection and maintenance by contact, removal of debris after natural disasters, delivery and transportation, stringing of power lines, and many others. Nowadays, these tasks are performed by human operators in very dangerous conditions, like on top of scaffolds or suspended by climbing ropes. The use of aerial robots would allow reducing the risk for the human operators and, at the same time, to reduce the cost associated with such operations. Given the relevance of the problem, many research labs and companies have been attracted to it. As a result, we can find many European projects with the scope of advancing in the aerial robotic field. In the following, we list some concluded and ongoing projects with corresponding goals:

- *ARCAS*[3]: conceive aerial robots for assembly and construction of structures;
- *AEROARMS*[4]: design and build UAVs with high manipulation capabilities for industrial inspection and maintenance;
- *AEROWORKS*[5]: provide heterogeneous and collaborative aerial robotic workers for inspection and maintenance tasks in infrastructure environments;
- *ARCOW*[6]: design aerial co-workers helping humans in manufacturing processes;
- *AEROBI*[7]: conceive aerial vehicles for in-depth structural inspection of concrete bridges;
- *AIROBOTS*[8]: design aerial robots for remote inspection by contact;
- *HYFLIERS*[9]: conceive a robot with hybrid air and ground mobility with a long-reach hyper-redundant manipulator.

For the aimed goals, aerial vehicles need new manipulation capabilities to safely and reliably interact with the environment. This opens the door to new challenges in aerial robotics. An aerial manipulator, being a floating body, has to *actively* react to interaction forces with the environment, that have to be carefully taken into account. Indeed they could eventually destabilize the system. This is different for a grounded manipulator which *passively* reacts to interaction forces thanks to the ground constraint. Furthermore, for grounded manipulators, we can usually directly and accurately control the torque that each motor applies to the corresponding joint. For an aerial vehicle, we instead control (in first approximation) the spinning velocity of a rotating propeller that, by the aerodynamic effects, produces a force. Due to the complexity of the aerodynamic effects and to disturbances, it is not easy to precisely

[3]http://www.arcas-project.eu/.

[4]https://aeroarms-project.eu/.

[5]http://www.aeroworks2020.eu/.

[6]http://www.euroc-project.eu/index.php?id=grvc-catec.

[7]http://www.aerobi.eu/.

[8]http://airobots.dei.unibo.it/.

[9]http://www.oulu.fi/hyfliers/.

control these forces. these actuation errors drastically impact the performance of the robot while interacting with the environment. Finally, in order to improve the dexterity and the manipulation capability of aerial robots, the latter are usually endowed with interactive tools such as grippers or articulated arms. The final aerial manipulator results to be a complex system characterized by a complicated and in general highly nonlinear dynamics. The latter has to be carefully considered because the couplings between the aerial robot and the interacting tool, if not properly addressed, can easily bring the system into instability. As a consequence, new control methods have to be conceived considering the full dynamics of the system, in order to preserve the stability during the interaction phases as well.

The most simple tool that one can use is a *rigid tool* rigidly attached to the robot. This allows exchanging forces with the environment, e.g., by pushing or sliding. Although the tool is very simple in itself, the underactuation of the vehicle makes the physical interaction very challenging. To address the problem, the works in [13–15] designed a hybrid force/position control. The tool can be then equipped with a *gripper* in order to allow pick and place operations [16]. To further increase the manipulation and the payload capabilities, several aerial robots endowed with a simple rigid link or a gripper can manipulate an object in a coordinated fashion, as a sort of “flying-hand” [17–19].

Another very used and still simple interaction tool is a *cable*. The use of a cable allows partially decoupling the rotational dynamics of the vehicle with respect to the one of the load. However, the control authority on the load positioning is reduced and a particular attention has to be given to undesired load oscillations that might destabilize the system. Several works addressed the problems from the control point of view proposing, for example, adaptive controllers [20, 21], a hierarchical controller [22], a flatness-based geometric controller [23] and even a reinforcement learning based approach [24]. Other works instead, addressed the problem from a motion planning point of view proposing algorithms that generate optimal trajectories that minimize the load swing [25, 26]. Also, in this case, the multi-robot approach can be beneficial to increase the payload of the system and the control authority on the load [27–32]. Furthermore, cables are not only used for the transportation of goods but also to tether aerial vehicles to fixed or moving platforms in order to enhance the flight stability during strong wind conditions or during dangerous maneuvers like takeoff and landing on moving vehicles [33, 34]. An introduction on the tethered aerial vehicle is provided in the following Sect. 1.2.

Finally, one can endow the aerial vehicle with one or even more *articulated arms*. The employ of a so-called *aerial manipulator* (AM) allows reaching high levels of dexterity. Depending on the number of degrees of freedom, an object can be locally manipulated independently from the motion of the platform. If the system is overactuated, one can exploit the robot redundancy to achieve secondary tasks or to better compensate for external disturbances or tracking errors of the aerial vehicle. Nevertheless, the system results to be very complex and the underactuation of the vehicle makes its control even more complex. The easiest way to control such AM is with a *decentralized approach*. It consists of assuming the aerial vehicle and the robotic arm as two independent systems, considering the interaction forces as disturbances that have to be rejected. Indeed, the controller used for both subsystems is often a robust control [35, 36]. these methods can be also applied to robotic arms with kinematically controlled motors. However, they best perform only in quasi-static motions, i.e., when the couplings effects between the aerial vehicle and the articulated arm are practically negligible. As soon as the motion is more demanding in terms of accelerations, decentralized control methods fail, or in the best case show large tracking errors. In these cases is more advisable to use a *centralized control method* that considers the system as a unique entity. The centralized controllers proposed in the state of the art are strongly model-based and consider the full dynamics of the system [37–39]. If the kinematic and dynamic model is very well known, then centralized controllers can lead to very good performance. However, since they are strongly model based, as soon as there are some parameter uncertainties, the performance degrades. Furthermore, they often require torque controlled motors that are in general unfeasible for aerial manipulators due to the limited payload. A complete survey on the topic has also been recently published [40].

The previously mentioned examples address the aerial physical interaction problem using underactuated unidirectional-thrust vehicles. As already said this makes physical interaction tasks very challenging and prone to instability. However, a very recent and promising trend is to use *multidirectional-thrust aerial vehicles* instead [41]. As the name says, these vehicles can produce a thrust force in many directions with respect to the body frame. This means that they can independently control both position and orientation and can react to external disturbances almost instantaneously, when far from input saturation. These two great features make multidirectional-thrust aerial vehicles perfectly suited for physical interaction tasks since they are more robust to interaction forces and have more dexterity as well [42]. However, such benefit comes with the cost of a higher power consumption. In order to produce the thrust in several directions, the propellers are tilted or can be actively turned, toward different directions producing internal forces that waste energy. On the other hand, unidirectional-aerial vehicles are the most efficient in terms of energy. That is why it is still interesting to study aerial physical interaction by means of unidirectional-thrust vehicles.

Another important aspect of aerial physical interaction is related to motion planning. Even if we can control very well our robot, the trajectory for the execution of a certain task has to be carefully computed using motion planning techniques. To perform the task in a safe way, the planned trajectory must avoid obstacles and has to satisfy the intrinsic constraints of the considered robot. In particular, it has to be suitable for the dynamics of the system and its actuation limits. Classical motion planning methods rely on quasi-static assumptions and are based only on geometric and kinematic models of the system. Hence they are inadequate to achieve manipulation tasks involving physical interaction. In fact, when the robot is in contact with the environment and exchanges forces with it, the dynamics of the system cannot be neglected. This requires the use of a kinodynamic motion planning approach (e.g., [43]). However, kinodynamic planners developed so far are suitable only for simple systems, characterized by a small number of degrees of freedom and a relatively simple dynamic model, like car-like vehicles or quadrotors. Instead, in the context of aerial physical interaction, robots have usually a large number of degrees of freedom to increase the dexterity of the system. This, in turn, makes the motion planning problem very challenging, requiring the design of new kinodynamic motion planning methods. these have to cope with the nonlinear dynamics of the robot, its redundancy and the forces exchanged with the environment during manipulation tasks. Finally, the problem has to be solved very rapidly in order to use the planner online and to replan the trajectory in case of unforeseen events or moving obstacles. Some attempts to solve the motion planning problem for some specific cases can be found in [44, 45].

1.2 Tethered Aerial Vehicles

In the vast domain of UAVs, cables are not only used for single and cooperative transportation of goods. They are also used to tether the aerial vehicle to a ground station. Especially in the industrial sector, the link is mainly used as an umbilical device to provide power to the robot [46], and a high bandwidth communication channel with the base station. The possibility to power the robot directly from the ground station makes the aerial vehicle flight time theoretically infinite, overcoming one of the major limits of aerial robots. As a result, tethered aerial vehicles becomes suitable for many applications that require long operation time like monitoring [47], surveillance, aerial photography, communication reinforcement [48] and so on. The time flight provided by a single on-board battery would not be enough to fully accomplish the previous mentioned tasks. The great potentials of tethered aerial systems and their obtained big interest, is proven by the increasing number of private companies appeared in the market proposing tethered UAVs or power tether systems for standard commercial UAVs. Figure 1.1 gathers some of the many examples that one can find on-line.

(a) Courtesy of: Atlanta Instrumentation and Measurement, `www.aimatlanta.com`; and Guided Systems Technologies, `http://guidedsys.com`.

(b) Courtesy of: Elistair `www.elistair.com`.

(c) Elistair `www.elistair.com`. Copyright authorization in progress.

Fig. 1.1 Examples of companies proposing tethered aerial robots for long flight time operations

(a) Courtesy of: Apellix, http://www.apellix.com/

(b) Courtesy of: Aerones, www.aerones.com

Fig. 1.2 Examples of tethered aerial robots for cleaning applications

Another interesting use of the tether is to bring to the robot some sort of fluid for various type of applications, e.g., cleaning, painting or applying chemical products. Indeed, often there is the need of cleaning some part of a civil or industrial structure at high altitude, e.g. the windows of a skyscraper, the blades of a wind turbine, or the chimney of a refinery. Normally, these operations are conducted by human operators reaching the working spot by the use of climbing cords or by bulky and expensive scaffolds. Firstly, the use of an aerial robot in these applications would allow to perform the operation in an fully or semi autonomous mode reducing the risks for the human operators. Secondly, it would decrease the time and the costs related to the construction and deployment of scaffolds or climbing gears. However, due to the limited payload of standard aerial vehicles, it is practically unfeasible to carry on-board all the tools needed for these kind of tasks, e.g., a spying tool and a tank of detergent liquid. On the other hand, the tether could be made such that to provide to the robot not only the power to fly indefinitely, but the cleaning liquid as well. Figure 1.2 shows the tethered aerial vehicles proposed by two companies for the cleaning of a facade of an industrial structure, and the blades of a wind turbine, respectively.

In the previous mentioned cases, the cable is slack, i.e., there is not tension along the link. Therefore, except for its weight and inertia, the cable does not influence the motion of the aerial vehicle. In these cases, complex control strategy are not really needed and a standard position controller (or a tele-operation framework) can be used to perform the sought task.

The case in which the cable is taut is definitely more interesting from a scientific point of view. In this case there is a clear physical interaction between the aerial vehicle, the link itself, and the other end of the link. A taut cable can provide advantages that go beyond the ones already mentioned, such as: (i) improved flight stability and reliability, especially during dangerous maneuver or in the presence of strong wind [33], (ii) physical interaction with a ground object and (iii) stabilization with a minimal set of sensors, even in a GPS-denied environment [34, 49]. Examples of

(a) EC-SAFEMOBIL Copyright authorization in progress.

(b) FotoKite. Copyright authorization in progress.

Fig. 1.3 Examples of applications of tethered aerial vehicles when the cable is taut. In particular, starting from the left image: landing/takeoff on/from a moving platform and indoor inspection (a) Courtesy of: EC-SAFEMOBIL [53–55] (b) Courtesy of: FotoKite www.fotokite.com

application fields related to this kind of robotic systems exploiting the tautness of the cable are landing/taking-off from/on moving or sloped platforms [33, 50–52], inspection in GPS-denied environments, human-robot interaction [34] and stringing of power transmission lines (see Fig. 1.3 for some examples).

Notice that, since the link is taut, the dynamics of the aerial vehicles changes. Indeed the interaction force consisting in the internal force along the link has to be considered. Control and estimation for an aerial system that is connected by a taut cable to the ground is not an easy task. In fact, standard flight-control and estimation methods either cannot be applied straightforwardly to this case or, if applicable, provide only sub-optimal performance, because they do not exploit the full dynamics and capabilities available to the new interconnected system. Therefore, the only way to cope with the difficulties of the new robotic system and to exploit at best its capabilities is to design new control and estimation methods that consider the new system as whole. However this is hard to accomplish, due to the nonlinear dynamics and the dynamic coupling between the aerial vehicle and the link.

For a complete understanding of these type of robotic systems, this book aims at providing a deep and thorough theoretical analysis which is the basis for solving practical problems related to real applications. In particular, we shall consider the most generic tethered aerial system, i.e., a generic unidirectional-thrust aerial vehicle flying in the 3D space and tethered to a freely moving platform by a generic link (not only by a cable), together with a link actuator able to change its length. For this system, we shall investigate its dynamics and its intrinsic properties, such as the *differential flatness*. This property is very useful both for control and motion planning. Indeed the analysis of such property allows understanding which are the outputs, called *flat* *outputs*, that can be independently controlled and which is their required degree of smoothness. Furthermore, it provides the tools to analytically compute the nominal state and input required to track a desired trajectory of the flat output. This turns out to be very helpful in the motion planning phase to simplify the planning method and to check for the feasibility of the desired trajectory. These results will be the base to design different types of *controllers for tracking* the outputs of interest. To close the control loop, the full state of the system is required. Practically, having a direct measurement of the state is often unfeasible. In this work we shall then considered the problem of closing the control loop with a minimal set of sensors, investigating the *observability*, and designing a *global nonlinear observer*.

Finally, we will try to apply the presented theoretical results to a real application problem. In particular we shall consider the practical problem of *takeoff and landing from/on a sloped surface*. For a standard unidirectional-thrust vehicle in a free-flight configuration, this is a very challenging problem. On the other hand, we will theoretically and experimentally show that the use of the tether makes the execution of these maneuvers much safer, reliable and robust to tracking errors and parameters uncertainties.

1.3 Organization of the Book

In this section, we provide a reader's guide describing the organization of the book and summarizing the content of each chapter.

The first three chapters provide the preliminaries to better contextualize this work in the field of aerial physical interaction, and the mathematical methodologies to better understand the core part. In particular,

Chapter 2 recalls in a synthetic way the mathematical methodologies used as background for the theoretical analysis of tethered aerial vehicles. In particular, we revise the two most used modeling methods, i.e., Lagrangian and Newton-Euler formalisms, the differential flatness property, the dynamic feedback linearization control, and the nonlinear high gain observer.

Chapter 3 provides the models of the subsystems, actuators, and sensors composing the studied generic tethered aerial vehicle. We provide the generic model of an unidirectional-thrust aerial vehicle in free-flight, the model for its propellers and onboard sensors. A model of a generic link and of an encoder are also provided.

Chapters from 4 to 6 represent the main body of the book, namely the complete and exhaustive study of aerial tethered vehicles. This analysis starts with the modeling of the system and passes through the characterization of its dynamic properties such as the differential flatness, controllability, and observability using a minimal sensory setup. The results of an experimental and simulation campaign are presented to validate the proposed methods. These are also used as a base for solving the more applicative problem of landing and takeoff on/from a sloped surface. In particular, we shall show that the use of a tether makes the execution of such dangerous maneuvers much more safe, reliable and robust to model uncertainties and tracking errors. Finally, a multi-robot extension is considered for which we performed a thorough theoretical analysis similar to the one for the single-tethered case. This part gathers the work of several articles and some unpublished results as well. For the sake of homogeneity, completeness, and clarity, in this book we present a complete dissertation of the topic based on a very detailed reworking of the content of the several publications.

Chapter 4 contains the complete and thorough theoretical study of a single tethered aerial vehicle. We provide the model of a generic system. For such a system we investigate the differential flatness and which are the flat outputs. For the latter, we design a hierarchical controller and another controller based on dynamic feedback linearization for the tracking of any desired trajectory. Finally, we investigate the problem of closing the control loop with a minimal sensory setup.

Chapter 5 presents all the results obtained from an extensive experimental and numerical campaign apt to validate the proposed methods.

Chapter 6 shows the study of the challenging and application-oriented problem of landing and takeoff on/from a sloped surface. For this problem, we theoretically and experimentally show that the use of the tether is advisable, when possible. Indeed, it allows executing these maneuvers in a much more robust and reliable way.

Chapter 7 analyzes an interesting multi-robot extension of the single tethered system. This system is similar to a 2-links planar manipulator where the actuators are aerial vehicles connected in a chain-like configuration. For this system, similarly to the single-robot system, we analyze the differential flatness, the controllability by dynamic feedback linearization and the observability using a minimal set of sensors.

The book concludes with Chap. 8:

Chapter 8 provides a global overview of the book, together with some discussions about the obtained results. Potential future applications and extensions of this work are considered as well.

References

1. Feron, E., Johnson, E.N.: Aerial robotics. In: Springer Handbook of Robotics, pp. 1009–1029. Springer (2008)
2. Economist, T.: Welcome to the Drone Age, Sept (2015). [Online]
3. Morin, P.: Modeling and control of convertible micro air vehicles. In: 2015 10th International Workshop on Robot Motion and Control (RoMoCo), pp. 188–198. IEEE (2015)
4. Hua, M.-D., Hamel, T., Morin, P., Samson, C.: Control of VTOL vehicles with thrust-tilting augmentation. Automatica **52**, 1–7 (2015)
5. Plinval, H., Morin, P., Mouyon, P., Hamel, T.: Visual servoing for underactuated VTOL UAVs: a linear, homography-based framework. Int. J. Robust Nonlinear Control **24**(16), 2285–2308 (2014)

6. Faessler, M., Franchi, A., Scaramuzza, D.: Differential flatness of quadrotor dynamics subject to rotor drag for accurate tracking of high-speed trajectories. IEEE Robot. Autom. Lett. **3**(2), 620–626 (2018)
7. Lee, T., Leoky, M., McClamroch, N.H.: Geometric tracking control of a quadrotor UAV on SE(3). In: 49th IEEE Conference on Decision and Control, pp. 5420–5425. Atlanta, GA, Dec (2010)
8. Ollero, A., Merino, L.: Control and perception techniques for aerial robotics. Annu. Rev. Control **28**(2), 167–178 (2004)
9. Valavanis, K.P., Vachtsevanos, G.J.: Future of unmanned aviation. In: Handbook of Unmanned Aerial Vehicles, pp. 2993–3009. Springer (2015)
10. Mahony, R., Kumar, V., Corke, P.: Multirotor aerial vehicles: modeling, estimation, and control of quadrotor. IEEE Robot. Autom. Mag. **19**(3), 20–32 (2012)
11. Hua, M.-D., Hamel, T., Morin, P., Samson, C.: Introduction to feedback control of underactuated VTOL vehicles: a review of basic control design ideas and principles. IEEE Control Syst. Mag. **33**(1), 61–75 (2013)
12. Hua, M.-D., Hamel, T., Morin, P., Samson, C.: A control approach for thrust-propelled underactuated vehicles and its application to VTOL drones. IEEE Trans. Autom. Control **54**(8), 1837–1853 (2009)
13. Nguyen, H., Lee, D.: Hybrid force/motion control and internal dynamics of quadrotors for tool operation. In: 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 3458–3464, Tokyo, Japan, Nov (2013)
14. Bartelds, T., Capra, A., Hamaza, S., Stramigioli, S., Fumagalli, M.: Compliant aerial manipulators: toward a new generation of aerial robotic workers. IEEE Robot. Autom. Lett. **1**(1), 477–483 (2016)
15. Gioioso, G., Mohammadi, M., Franchi, A., Prattichizzo, D.: A force-based bilateral teleoperation framework for aerial robots in contact with the environment. In: 2015 IEEE International Conference on Robotics and Automation, pp. 318–324, Seattle, WA, May (2015)
16. Mellinger, D., Lindsey, Q., Shomin, M., Kumar, V.: Design, modeling, estimation and control for aerial grasping and manipulation. In: 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 2668–2673, San Francisco, CA, Sept (2011)
17. Mellinger, D., Shomin, M., Michael, N., Kumar, V.: Cooperative grasping and transport using multiple quadrotors. In: 10th International Symposium on Distributed Autonomous Robotic Systems, pp. 545–558, Lausanne, Switzerland, Nov (2010)
18. Gioioso, G., Salvietti, G., Franchi, A., Malvezzi, M., Scheggi, S., Meli, L., Ryll, M., Bülthoff, H.H., Prattichizzo, D.: The flying hand: a teleoperation framework for cooperative aerial grasping and transportation. In: Automatica.it 2014, Convegno Annuale dei Docenti e Ricercatori Italiani in Automatica, Bergamo, Italy, Sept (2014)
19. Staub, N., Mohammadi, M., Bicego, D., Prattichizzo, D., Franchi, A.: Towards robotic MAGMaS: multiple aerial-ground manipulator systems. In: 2017 IEEE International Conference on Robotics and Automation, Singapore, May (2017)
20. Dai, S., Lee, T., Bernstein, D.S.: Adaptive control of a quadrotor UAV transporting a cable-suspended load with unknown mass. In: 2014 IEEE 53rd Annual Conference on Decision and Control (CDC), pp. 6149–6154. IEEE (2014)
21. Palunko, I., Cruz, P., Fierro, R.: Agile load transportation: safe and efficient load manipulation with aerial robots. IEEE Robot. Autom. Mag. **19**(3), 69–79 (2012)
22. Bernard, M., Kondak, K., Maza, I., Ollero, A.: Autonomous transportation and deployment with aerial robots for search and rescue missions. J. Field Robot. **28**(6), 914–931 (2011)
23. Sreenath, K., Lee, T., Kumar, V.: Geometric control and differential flatness of a quadrotor UAV with a cable-suspended load. In: 2013 IEEE 52nd Annual Conference on Decision and Control (CDC), pp. 2269–2274. IEEE (2013)
24. Palunko, I., Faust, A., Cruz, P., Tapia, L., Fierro, R.: A reinforcement learning approach towards autonomous suspended load manipulation using aerial robots. In: 2013 IEEE International Conference on Robotics and Automation (ICRA), pp. 4896–4901. IEEE (2013)

25. Sreenath, K., Michael, N., Kumar, V.: Trajectory generation and control of a quadrotor with a cable-suspended load-a differentially-flat hybrid system. In: 2013 IEEE International Conference on Robotics and Automation (ICRA), pp. 4888–4895. IEEE (2013)
26. Foehn, P., Falanga, D., Kuppuswamy, N., Tedrake, R., Scaramuzza, D.: Fast trajectory optimization for agile quadrotor maneuvers with a cable-suspended payload. In: Robotics: Science and Systems, pp. 1–10 (2017)
27. Sreenath, K., Kumar, V.: Dynamics, control and planning for cooperative manipulation of payloads suspended by cables from multiple quadrotor robots. In: Robotics: Science and Systems, Berlin, Germany, June (2013)
28. Manubens, M., Devaurs, D., Ros, L., Cortés, J.: Motion planning for 6-D manipulation with aerial towed-cable systems. In: Robotics: Science and Systems, p. 2013. Germany, May, Berlin (2013)
29. Maza, I., Kondak, K., Bernard, M., Ollero, A.: Multi-UAV cooperation and control for load transportation and deployment. J. Intell. Robot. Syst. **57**(1–4), 417–449 (2010)
30. Gabellieri, C., Tognon, M., Sanalitro, D., Palottino, L., Franchi, A.: A study on force-based collaboration in swarms. Swarm Intell. **14**, 57–82 (2020)
31. Tognon, M., Gabellieri, C., Pallottino, L., Franchi, A.: Aerial co-manipulation with cables: the role of internal force for equilibria, stability, and passivity. IEEE Robot. Autom. Lett. Spec. Issue Aerial Manip. **3**(3), 2577–2583 (2018)
32. Sanalitro, D., Savino, H.J., Tognon, M., Cortés, J., Franchi, A.: Full-pose manipulation control of a cable-suspended load with multiple UAVs under uncertainties. Under review in IEEE Robotics and Automation Letters (2020)
33. Sandino, L.A., Bejar, M., Kondak, K., Ollero, A.: Advances in modeling and control of tethered unmanned helicopters to enhance hovering performance. J. Intell. Robot. Syst. **73**(1–4), 3–18 (2014)
34. Lupashin, S., D'Andrea, R.: Stabilization of a flying vehicle on a taut tether using inertial sensing. In: 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 2432–2438, Tokyo, Japan, Nov (2013)
35. Siciliano, B., Sciavicco, L., Villani, L., Oriolo, G.: Robotics: Modelling. Springer, Planning and Control (2009)
36. Ruggiero, F., Trujillo, M.A., Cano, R., Ascorbe, H., Viguria, A., Peréz, C., Lippiello, V., Ollero, A., Siciliano, B.: A multilayer control for multirotor UAVs equipped with a servo robot arm. In: 2015 IEEE International Conference on Robotics and Automation, pp. 4014–4020, Seattle, WA, May (2015)
37. Yang, H., Lee, D.J.: Dynamics and control of quadrotor with robotic manipulator. In: 2014 IEEE International Conference on Robotics and Automation, pp. 5544–5549, Hong Kong, China, May (2014)
38. Yüksel, B., Staub, N., Franchi, A.: Aerial robots with rigid/elastic-joint arms: single-joint controllability study and preliminary experiments. In: 2016 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 1667–1672, Daejeon, South Korea, Oct (2016)
39. Mersha, A.Y., Stramigioli, S., Carloni, R.: Exploiting the dynamics of a robotic manipulator for control of UAVs. In: 2014 IEEE International Conference on Robotics and Automation (ICRA), pp. 1741–1746. IEEE (2014)
40. Ruggiero, F., Lippiello, V., Ollero, A.: Aerial manipulation: a literature review. IEEE Robot. Autom. Lett. **3**(3), 1957–1964 (2018)
41. Rajappa, S., Ryll, M., Bülthoff, H.H., Franchi, A.: Modeling, control and design optimization for a fully-actuated hexarotor aerial vehicle with tilted propellers. In: 2015 IEEE International Conference on Robotics and Automation, pp. 4006–4013, Seattle, WA, May (2015)
42. Ryll, M., Muscio, G., Pierri, F., Cataldi, E., Antonelli, G., Caccavale, F., Franchi, A.: 6D physical interaction with a fully actuated aerial robot. In: 2017 IEEE International Conference on Robotics and Automation, pp. 5190–5195, Singapore, May (2017)
43. Boeuf, A., Cortés, J., Alami, R., Siméon, T.: Enhancing sampling-based kinodynamic motion planning for quadrotors. In: 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 2447–2452, Hamburg, Germany, Sept (2015)

44. Lee, H., Kim, H., Kim, H.J.: Planning and control for collision-free cooperative aerial transportation. IEEE Trans. Autom. Sci, Eng (2016)
45. Fink, J., Michael, N., Kim, S., Kumar, V.: Planning and control for cooperative manipulation and transportation with aerial robots. Int. J. Robot. Res. **30**(3), 324–334 (2011)
46. Choi, S.Y., Choi, B.H., Jeong, S.Y., Gu, B.W., Yoo, S.J., Rim, C.T.: Tethered aerial robots using contactless power systems for extended mission time and range. In: Energy Conversion Congress and Exposition (ECCE), 2014 IEEE, pp. 912–916. IEEE (2014)
47. Muttin, F.: Umbilical deployment modeling for tethered UAV detecting oil pollution from ship. Appl. Ocean Res. **33**(4), 332–343 (2011)
48. Pinkney, M.F., Hampel, D., DiPierro, S.: Unmanned aerial vehicle (UAV) communications relay. In: Military Communications Conference, 1996, vol. 1, pp. 47–51, Oct (1996)
49. Sandino, L., Santamaria, D., Bejar, M., Viguria, A., Kondak, K., Ollero, A.: Tether-guided landing of unmanned helicopters without GPS sensors. In: 2014 IEEE International Conference on Robotics and Automation, pp. 3096–3101, Hong Kong, China, May (2014)
50. Tognon, M., Dash, S.S., Franchi, A.: Observer-based control of position and tension for an aerial robot tethered to a moving platform. IEEE Robot. Autom. Lett. **1**(2), 732–737 (2016)
51. Tognon, M., Testa, A., Rossi, E., Franchi, A.: Takeoff and landing on slopes via inclined hovering with a tethered aerial robot. In: 2016 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 1702–1707, Daejeon, South Korea, Oct (2016)
52. Oh, S.-R., Pathak, K., Agrawal, S.K., Pota, H.R., Garrett, M.: Approaches for a tether-guided landing of an autonomous helicopter. IEEE Trans. Robot. **22**(3), 536–544 (2006)
53. EC-SAFEMOBIL. EU Coll. Proj. FP7-ICT 288082. http://www.ec-safemobil-project.eu/
54. Alarcón, F., García, M., Maza, I., Viguria, A., Ollero, A.: A Precise and GNSS-Free Landing System on Moving Platforms for Rotary-Wing UAVs. SensS. **19**(4), 886 (2019)
55. Sandino, Luis, A., Santamaria, D., Bejar, M., Kondak, K., Viguria, A., Ollero, A.: First experimental results on enhancing hovering performance of unmanned helicopters by using a tethered setup. Robot. Auton. Syst. **79**(4), 147–155 (2016)