Past, Present, and Future of Aerial Robotic Manipulators

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***Abstract*—This article analyzes the evolution and current trends in aerial robotic manipulation, comprising helicopters, conventional underactuated multirotors, and multidirectional thrust platforms equipped with a wide variety of robotic manipulators capable of physically interacting with the environment. It also covers cooperative aerial manipulation and interconnected actuated multibody designs. The review is completed with developments in teleoperation, perception, and planning. Finally, a new generation of aerial robotic manipulators is presented with our vision of the future.**

***Index Terms*—Aerial manipulation, aerial robots physically interacting with the environment, unmanned aerial vehicles.**

I. Introduction

THE field of aerial robots physically interacting with the environment, and particularly aerial robotic manipulators (AEROMs), has experienced ten years of sustained growth. Diverse prototypes, functionalities and capabilities have been developed and evaluated in representative indoor and outdoor scenarios, demonstrating the possibility to successfully perform manipulation tasks while flying. The ability of aerial manipulators to quickly reach and operate in high altitude workspaces, along with the level of maturity reached in recent years, led to the application of this technology in areas like inspection and maintenance, reducing time, cost, and risk for the human workers. In this sense, this article aims at providing a broad perspective and analysis of the work done in aerial manipulation, possibly helping engineers interested in designing an aerial manipulation robot for a specific task.

TABLE I
Generations of Aerial Robotic Manipulators

	1^{st} Gen.	2^{nd} Gen.	3^{rd} Gen.
Platforms	Helicopters Quadrotors	Helicopters Multi-rotors	Multi-rotors: fully actuated, multibody
Arms	Few DoFs	6/7 DoFs Compliance	Dual arms Hyper-redundant
Navigation	Motion tracking system	Indoor beacons GPS	SLAM
Perception	No onboard motion tracking	Onboard with markers	Onboard without markers
Planning	No planning	Ground station Basic reaction	On-board Reactivity

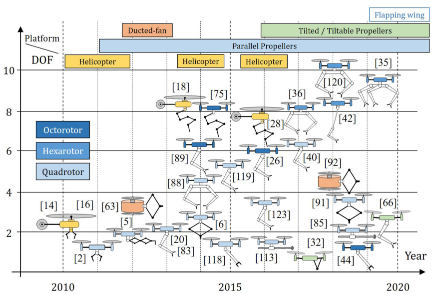

Fig. 1. Evolution in the development of aerial manipulation prototypes, comprising different platforms, and morphologies.

Reviewing the main achievements in this field, it is possible to identify common features that allow defining the classification proposed in Table I. Fig. 1 shows the evolution of aerial manipulator designs in the last decade, although early achievements can be also found in the 90 s with the disc lifting mission at the International Aerial Robotics Competition.[1] The first generation of aerial manipulators consisted of conventional quadrotors capable of applying forces to a wall while keeping flight stability [1], grasping objects [2], and constructing cubic structures [3] with an embedded arm with few degrees of freedom (DoFs). Less conventional designs started to appear: Marconi *et al.* [4]

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航空机械手的过去、现在和未来

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摘要本文分析了空中机器人操作的发展和当前趋势，包括直升机、Convent-
欠驱动多转子和多向推力平台-
表格配备了各种各样的机械手，能够与环境进行物理交互。它还包括协同空中操纵和互联驱动多体系统
设计。该审查随着远程操作、感知和规划的发展而完成。最后，新一代天线
机器人机器人展现了我们对未来的展望。

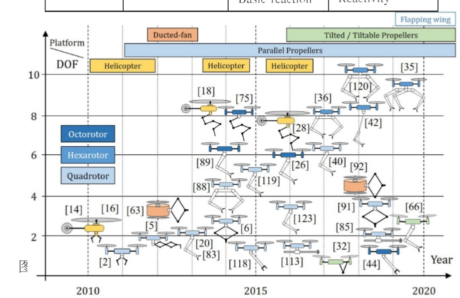
索引项空中操纵、空中机器人与环境的物理交互、无人机。

表I
几代航空机械手

	1^{st} Gen.	2^{nd} Gen.	3^{rd} Gen.
Platforms **Arms**	Helicopters Quadrotors Few DoFs	Helicopters Multi-rotors	Multi-rotors: fully actuated, multibody
	Motion tracking system	Indoor beacons GPS 6/7 DoFs Compliance	Dual arms Hyper-redundant SLAM
Navigation **Perception**			
Planning	No onboard motion tracking	Onboard with markers	Onboard without markers
	No planning	Ground station Basic reaction	On-board Reactivity

I. Introduction

T 与环境进行物理交互的航空机器人领域，尤其是航空机器人机械手（AEROMs），经历了十年的持续增长。在典型的室内和室外场景中开发和评估了各种原型、功能和能力，证明了在飞行时成功执行操纵任务的可能性。由于空中机械手能够快速到达高空工作区并在高空作业，加上近年来达到的成熟水平，这项技术被应用于检查和维护等领域，从而减少了人类工人的时间、成本和风险。从这个意义上讲，本文旨在提供一个广阔的视角，并分析在空中操纵方面所做的工作，



可能会帮助有兴趣为特定任务设计空中操纵机器人的工程师。

回顾这一领域的主要成就，可以确定允许定义表I中提出的分类的共同特征。图1显示了过去十年中航空机械手设计的演变，尽管早期的成就也可以在90年代国际航空机器人竞赛中的圆盘提升任务中找到。[1]第一代航空机械手由传统的四旋翼组成，能够在保持飞行稳定性的同时向墙壁施力[1],抓取物体[2],并通过嵌入的手臂构造具有几个自由度（自由度）的立方体结构[3]。较不传统的设计开始出现：Marconi等人【4】

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presented the modeling and control of a ducted-fan miniature UAV interacting with the environment; a six-DoFs gantry crane equipped with two four-DoFs manipulators was also proposed in [5]; and a three-active-DoFs delta-like manipulator with a three-passive-DoFs end-effector installed on a quadrotor was developed in [6]. These prototypes employed motion tracking systems for positioning in indoors [7]–[10], without relevant perception and planning.

Helicopters played an important role in the development of the aerial manipulation with early works in outdoors applied to load transportation [11]–[13], interaction with the environment [14], [15], and manipulation [16]–[18], showing better performance than multirotors in terms of payload capacity and operation time. However, the use of multirotors spread in following years because the control, mechanical construction, and handling of these platforms are significantly simpler, and allow to mitigate safety problems associated to the blades of the helicopters main rotor.

The second generation includes adapted aerial platforms for both indoor and outdoor operations, equipped with rigid and compliant arms (up to six/seven DoFs) for precise end-effector positioning and compensation of perturbations. They also integrate outdoor navigation sensors based on Global Navigation Satellite System (GNSS), indoor navigation features based on beacons, on-board perception with markers, and off-board planning features. Outdoor experiments involving grasping with seven-DoFs arms with both helicopters [19] and multirotors [20] were presented. Different arm designs have been introduced as well, including parallel manipulators with a large singularity-free workspace [21] for precise end-effector positioning relative to a target [22], or a hyper-redundant manipulator for mobile manipulating UAVs [23]. Attention was also paid to control techniques validated in simulation [24]. In [25], a framework for outdoor aerial manipulation is presented. Regarding vision-based controllers, a hybrid visual servoing with a hierarchical task-composition control is presented in [26]. An integrated vision-based guiding system for aerial manipulation with a stereo camera is shown in [27].

The current third generation of aerial manipulators includes several advanced features: operations in both outdoor/indoor environments [28], fully actuated platforms [29]–[32], multiple arms [33]–[36], GNSS free navigation capabilities, on-board SLAM [37], [38], on-board perception without markers [39], [40], off-board real-time planning with control awareness [41], [42], and on-board reactivity and planning. Applications include structure assembly, contact-based inspection in refineries (pipes and tanks), and bridges [43], [44].

The kinematics, dynamics, and control of AEROMs with conventional multirotor platforms is shown in [33]. Significant similarities can be established with space [45] and underwater [46], [47] manipulation in the formulation and derivation of the kinematic and dynamic models. The use of dual arm systems in aerial and space manipulation was motivated by the convenience of partially compensating reaction wrenches induced over the floating base due to the motion of the operating arm. We notice that the gravity effect is probably the most limiting factor in an aerial manipulation robot in terms of payload capacity and operation time [11], [48]. An analogy can be also drawn between the aerodynamic [49] and hydrodynamic [46] modeling in aerial and underwater manipulators. Previous surveys on modeling and control of multirotor vehicles [50] and aerial manipulators [51], [52], provide a very good baseline for this paper. Here, we extend them considering novel and more complex aerial platforms like flapping wing [53], [54], focusing not only on modeling and control methods, but also on teleoperation, perception, and motion planning techniques.

II. Platforms for Aerial Manipulation

Here, we introduce the spectrum of different platform designs that can be used for aerial manipulation. It includes helicopter, ducted-fan, and the most popular multirotor platforms. In our review, we group platforms by types, i.e., clusters defined according to major design characteristics. The platforms will be additionally clustered according to the actuation property, type of interaction tool, and performed tasks. We also review the popular control algorithms used to stabilize and steer these systems during physical interaction.

A. Modeling and Actuation Properties

Here, we consider a rather general definition of *multirotor platforms* with a main body equipped with $n \in \mathbb{N}_{>0}$ actuators consisting of a motor-propeller pair that produces a thrust and a drag moment on the main body. Their intensities are proportional to the square of the propeller spinning velocity, $u_{\lambda_i} = |w_i| w_i \in \mathbb{R}$ [50]. We gather all control inputs related to the thrust intensity in $\boldsymbol{u}_\lambda \in \mathbb{R}^n$. With respect to (w.r.t.) the body frame $\mathcal{B}$ attached to the main body, each propeller can be shown as follows:

1) *rigidly fixed*;
2) *tiltable* by $m \leq 2n$ servomotors where $\boldsymbol{u_V} \in \mathbb{R}^m$ gathers their angular positions controlling the orientation of the propeller spinning axes;
3) *movable* by $r \leq 3n$ servomotors where $\boldsymbol{u_P} \in \mathbb{R}^r$ gathers their angular positions controlling the position of the propellers.

The dynamics of a generic multirotor is computed in [50]. One important element is the *full allocation matrix*, $\boldsymbol{F}(\boldsymbol{u}_\lambda, \boldsymbol{u_V}, \boldsymbol{u_P}) \in \mathbb{R}^{6\times(n+m+r)}$. It defines how an input variation affects the total wrench generated by the platform. In [50], the analysis of $\boldsymbol{F}$ brought to the definition of actuation properties that characterize the set of feasible wrenches.

1) Uni-Directionnal Thrust (UDT): Platforms with this property can vary the total thrust along one direction only (like in coplanar/parallel designs, helicopters, and ducted-fans). We say that a platform is UDT if $\text{rank}\{\boldsymbol{F}\} = 4$. For helicopters and ducted-fan vehicles, the previous model does not apply directly. In general, the total thrust and torque are considered as inputs [16], [18]. Since the direction of thrust is constant w.r.t. body frame, the corresponding allocation matrix has rank 4, which makes such vehicles UDT.

2) Multidirectionnal Thrust (MDT): Platforms with this property can vary the total thrust along more than one direction independently from the total moment. We say that a platform is MDT if $5 \leq \text{rank}\{\boldsymbol{F}\} \leq 6$.

3) Fully Actuated (FA): This describes a subclass of MDT platforms. Platforms with this property can vary the total thrust along all directions independently from the total moment. We say that a platform is FA if $\text{rank}\{\boldsymbol{F}\} = 6$.

这篇文章已被接受收录在本刊未来的一期中。除分页外，内容均为最终内容。

介绍了与环境相互作用的管道风扇微型无人机的建模与控制；[5]中还提出了配备两个四自由度机械手的六自由度龙门起重机；[6]中开发了一种三主动自由度三角形机械手，在四旋翼上安装了一个三被动自由度末端执行器。这些原型使用运动跟踪系统在室内进行定位[7]–[10],没有相关的感知和规划。

直升机在空中操纵的发展中发挥了重要作用，早期的户外工作应用于载荷运输[11]–[13]、与环境的相互作用[14]、[15]和操纵[16]–[18],在有效载荷容量和操作时间方面表现出比多旋翼机更好的性能。然而，由于这些平台的控制、机械结构和操作都非常简单，并且能够缓解与直升机主旋翼叶片相关的安全问题，因此多旋翼的使用在接下来的几年中得到了推广。

第二代包括适应室内和室外操作的空中平台，配备刚性和柔顺臂（最多六/七个自由度），用于精确的末端执行器定位和扰动补偿。它们还集成了基于全球导航卫星系统（GNSS）的室外导航传感器、基于信标的室内导航功能、带标记的车载感知功能和非车载规划功能。介绍了使用直升机[19]和多旋翼[20]用七个自由臂抓取的户外实验。还引入了不同的手臂设计，包括具有大型无奇异工作空间[21]的并联机械手，用于相对于目标精确定位末端执行器[22],或用于移动操作无人机的超冗余机械手[23]。还注意了在模拟中验证的控制技术[24]。在[25]中，提出了一个户外空中操纵的框架。关于基于视觉的控制器，在[26]中提出了一种带有分层任务合成控制的混合视觉伺服。[27]中显示了一个集成的基于视觉的引导系统，用于立体相机的空中操作。

目前的第三代空中操纵器包括
几个高级功能：在室外/室内环境中的操作[28]、全驱动平台[29]–[32]、多臂[33]–[36]、无GNSS导航能力、车载SLAM [37]、[38]、无标记的车载感知[39]、[40]、具有控制感知的非车载实时规划[41]、[42]以及车载反应性和规划。应用包括结构组装、炼油厂（管道和储罐）的接触式检查以及桥梁[43], [44]。

[33]显示了具有传统多转子平台的AEROMs的运动学、动力学和控制。在运动学和动力学模型的制定和推导过程中，空间[45]和水下[46], [47]操纵可以建立显著的相似性。在空中和空间操纵中使用双臂系统的动机是，由于操作臂的运动，在浮动底座上产生了部分补偿反作用扳手。我们注意到，就有效载荷容量和操作时间而言，重力效应可能是空中操纵机器人的最大限制因素[11], [48]。空气动力学[49]和水动力学[46]建模之间也可以进行类比还有水下操纵器。之前关于多转子飞行器[50]和航空机械手[51]、[52]建模和控制的研究为本文提供了一个很好的基础。在这里，我们考虑到扑翼[53]、[54]等新型和更复杂的空中平台，对其进行了扩展，不仅关注建模和控制方法，还关注遥操作、感知和运动规划技术。

二、Platforms for Aerial Manipulation

这里，我们介绍不同平台设计的频谱
可以用于空中操纵。它包括直升机、管道风扇和最流行的多旋翼平台。在我们的综述中，我们按类型对平台进行分组，即根据主要设计特征定义的集群。平台将根据驱动特性、交互工具类型和执行的任务进行额外集群。我们还回顾了在物理交互过程中用于稳定和控制这些系统的流行控制算法。

A.建模和驱动特性

这里，我们考虑多转子平台的一个相当一般的定义，该平台的主体配备有n N>0个执行器，执行器∈由一对电机-螺旋桨组成，在主体上产生推力和阻力矩。它们的强度与螺旋桨旋转速度的平方成正比，u_{λ_i} = w_i w_i
R [50]。我们收集与推力强度相关的所有控制输入 | | ∈
在u_λ ∈ R^n。关于车身框架（w.r.t.） B 附在主体上的每个螺旋桨可以如下所示:

1) 固定的；
2) 可由m 2n伺服≤电机倾斜，其中u_V R^m收集∈其角度位置，控制螺旋桨旋转轴的方向；
3) 可通过r 3n伺≤服电机移动，其中u_P R^r收∈集其角度位置，控制螺旋桨的位置。

通用多转子的动力学计算见[50]。一个重要元素是完整的分配矩阵F（u_λ, u_V , u_P）$R^{6\times(n+m+r)}$。它定义了输入变量如何影响平台生成∈的总扳手。在[50]中,对F的分析得出了驱动特性的定义,该特性是一组可行扳手的特征。

1) 单向推力（UDT）：具有该特性的平台只能沿一个方向改变总推力（如共面/平行设计、直升机和管道风机）。如果秩F = 4. 我们说平台是UDT。对于直升机和管道风扇车辆，之前的型号不直接适用{ 。}通常，总推力和扭矩被视为输入[16. , [18. 。因为推力的方向是恒定的
w、 在r.t.车身框架中，相应的分配矩阵具有秩4,这使得此类车辆UDT。

2) 多向推力（MDT）：具有这种特性的平台可以独立于总力矩沿多个方向改变总推力。我们说一个平台是MDT如果5秩F 6。

3) 全驱≤动（F{A)} ≤这描述了MDT的一个子类
平台。具有该特性的平台可沿所有方向独立于总力矩改变总推力。如果秩{F } = 6，我们说平台是FA。

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4) Over Actuated (OA): With this property, we describe multirotor platforms that are FA and have more actuation inputs, $n_u = n + m + r$, than DoF. A multirotor is OA if it is FA and for each desired wrench there is more than one input combination that realizes it, i.e., $n_u > 6$.

5) Omni Directional (OD): This describes another subclass of FA designs, not exclusive from OA, where the total thrust can assume any value in a spherical shell independently from the total moment. A more detailed study on the theoretical characterization of OD multirotors with unidirectional propellers is provided in [31].

B. Control Methods for Contactless Tasks

If the platform is FA, the design of the controller is rather straightforward because the full allocation matrix $\boldsymbol{F}$ is invertible. This allows applying simple *static* (for fixed propellers) or *dynamic* (for tiltable and movable propellers) *feedback linearization* that allows the independent control of the position and orientation [55]. If the platform is OA, the null space of $\boldsymbol{F}$ can be used to optimize the control inputs [56].

If the platform is not FA, feedback linearization cannot be directly applied. A specific controller should be designed to face the underactuation. For quadrotors and helicopters, to apply dynamic feedback linearization a first input transformation is required considering the total thrust and moment as input.

Feedback linearizable systems are also differentially-flat [57]. It follows that any FA vehicles is differentially-flat w.r.t. position and orientation. Additionally, it has been proven that UDT vehicles, like quadrotors, ducted-fan, and helicopters, are also differentially-flat w.r.t. center-of-mass position and yaw angle. Therefore, every UDT and FA (as well as OA and OD) aerial platforms are differentially-flat, although with different flat outputs. Differential-flatness-based controllers can be used to control the robot position in contactless tasks.

The dynamics of the position of the center of mass of the full AEROM is decoupled from the orientational and postural dynamics, and it resembles the one of a UDT vehicle [58]. Therefore, AEROMs are differentially-flat systems with the global-center-of-mass position as flat output [59]. However, the end-effector position—the most relevant output for contact-based operations—is part of a flat output only for specific design of AEROMs [60], [61].

Other general methods that can be applied independently to FA and non-FA platforms are based on model predictive control (MPC). In [62], a nonlinear MPC-based controller, which considers the full nonlinear dynamics of the system and inputs constraints is proposed for any multirotor. However, a precise model of the system is required, as well as a fine tuning of the cost function. In practice, according to the complexity of the system, both requirements could be difficult to be obtained. In such cases, feedback linearization can be simpler to implement, especially in the static case.

C. Control Methods for Aerial Physical Interaction

When aerial vehicles are in interaction with the environment, they need to be able to control at the same time the position at the contact, and the interaction force, preserving the stability of the entire system. In the following, we review the most common control techniques designed for this scope.

1) Impedance/Admittance Control: This is probably the most common approach based on the reshaping of the impedance/admittance mechanical properties of the system at the interaction point. Impedance/admittance controllers establish a desired dynamical relationship between the end-effector position and the interaction force.

The *impedance control*, treats the system as a mechanical admittance. The input of the system is the force actuated by the robot and the output is the displacement of the end-effector. In practice, to perform contact-based tasks, the desired position of the end-effector is chosen "inside" the surface of interaction. The robot, trying to reach this point will generate a force that is related to the impedance properties of the controller. Such strategy has been proposed for both underactuated and fully-actuated aerial manipulators [63]–[68]. Notice that the compliance of the robot can be designed both software or hardware, by the controller or a suitable mechanical design [66], [69].

The *admittance control* is the dual of the impedance control. It treats the system as a mechanical impedance. The input of the system is the displacement of the end-effector and the output is the interaction force. Such strategy has been proposed for both underactuated and fully-actuated aerial manipulators [32], [70]–[75].

Passivity-based and *Port–Hamiltonian methods* have been also employed to design similar approaches, which aim at the reshaping of the apparent impedance/admittance properties of the system [76], [77].

2) Hybrid Position/Force Control: Previous schemes implement an indirect force control where the interaction force is indirectly controlled by designing a suitable end-effector trajectory. On the other hand, the hybrid position/force control method aims at precisely controlling the interaction force in a direct way. The robot is controlled by two complementary feedback loops, one for the position, the other for the interaction force, along the unconstrained and constrained axes, respectively. Such a control strategy has been implemented for UDT [60], [78]–[80], and FA [81] vehicles. In [82], a direct force-controller based on optimization is presented.

In order to implement the previously presented controllers, the estimation of the state (addressed in Section VII-B) and interaction forces are needed. For the latter, model-based wrench observers like the ones in [32] and [76], can be employed. A more direct solution is the use of a force sensor attached to the end-effector [70], [82]. This allows to implement a direct feedback in the interaction control loop.

We note that impedance/admittance controllers are very easy and intuitive to implement. Furthermore, the transition from contactless and contact-based flight can be easily handled with a smooth variation of the gains. However, precise interaction control is not guaranteed. On the other hand, hybrid position/force controllers can provide accurate position and force tracking but contact constraints have to be carefully addressed.

D. Physical Interaction Tasks

Here, we classify the physical interaction tasks addressed by the aerial robotic community. In particular, we consider only

这篇文章已被接受收录在本刊未来的一期中。除分页外，内容均为最终内容。

4) 过驱动（OA）：利用这一特性，我们描述了多转子平台，它们是FA，具有比DoF更多的驱动输入，$n_u = n + m + r$。如果多转子是FA，则多转子是OA，并且对于每个所需的扳手，有多个输入组合实现它，即$n_u > 6$。

5) Omni-directive（OD）：这描述了另一个子类

对于FA设计，不排除OA,其中总推力可以独立于总力矩假设球壳中的任何值。[31]中提供了关于带单向螺旋桨的OD多转子理论特性的更详细研究。

B. 非接触式任务的控制方法

如果平台是FA,控制器的设计相当简单，因为完整的分配矩阵F是可逆的。这允许应用简单的静态（用于固定螺旋桨）或动态（用于可倾斜和可移动螺旋桨）反馈线性化，允许独立控制位置和方向[55]。如果平台是OA,F的零空间可用于优化控制输入[56]。

如果平台不是FA,则不能直接应用反馈线性化。应设计一个特定的控制器，以应对欠驱动。对于四旋翼机和直升机，为了应用动态反馈线性化，需要考虑总推力和力矩作为输入进行第一次输入变换。

反馈线性化系统也是微分平坦的[57]。因此，任何FA车辆的位置和方向都是差平的。此外，已经证明，UDT车辆，如四旋翼、管道风扇和直升机，在重心位置和偏航角方面也是差异平坦的。因此，每个UDT和FA（以及OA和OD）空中平台都是不同的平坦平台，尽管具有不同的平坦输出。基于微分平面度的控制器可用于控制机器人在非接触任务中的位置。

全AEROM质心位置的动力学与方向和姿势动力学解耦，类似于UDT飞行器[58]。因此，AEROM是一种差分平坦系统，其整体质心位置为平坦输出[59]。然而，末端执行器位置——基于接触的操作最相关的输出是平面输出的一部分，仅适用于AEROMs的特定设计[60], [61]。

其他可独立应用于FA和非FA平台的通用方法基于模型预测控制（MPC）。在[62]中，针对任何多转子，提出了一种基于非线性MPC的控制器，该控制器考虑了系统的完全非线性动力学和输入约束。然而，需要系统的精确模型，以及成本函数的微调。在实践中，由于系统的复杂性，这两个需求可能都很难获得。在这种情况下，反馈线性化更容易实现，尤其是在静态情况下。

C. 空中物理交互的控制方法

当飞行器与环境相互作用时，它们需要能够同时控制接触点的位置和相互作用力，从而保持飞行器的稳定性整个系统。在下文中，我们将回顾针对这一范围设计的最常见的控制技术。

1) 阻抗/导纳控制：这可能是基于在相互作用点重塑系统阻抗/导纳机械特性的最常见方法。阻抗/导纳控制器在末端执行器位置和相互作用力之间建立所需的动力学关系。

阻抗控制将系统视为机械导纳。系统的输入是机器人驱动的力，输出是末端执行器的位移。在实践中，为了执行基于接触的任务，末端效应器的所需位置被选择在交互表面的"内部"。机器人试图达到这一点时，将产生与控制器阻抗特性相关的力。对于欠驱动和全驱动的航空机械手[63]–[68]都提出了这种策略。请注意，机器人的合规性可以通过控制器或合适的机械设计来设计软件或硬件[66], [69]。

导纳控制是阻抗控制的对偶。它将系统视为机械阻抗。系统的输入是末端执行器的位移，输出是相互作用力。对于欠驱动和全驱动的航空机械手[32]、[70]–[75]都提出了这种策略。

基于无源性和端口哈密顿方法也被用于设计类似的方法，旨在重塑系统的视在阻抗/导纳特性[76], [77]。

2) 混合位置/力控制：之前的方案实现了间接力控制，通过设计合适的末端执行器轨迹间接控制交互力。另一方面，混合位置/力控制方法旨在直接精确控制相互作用力。机器人由两个互补反馈回路控制，一个用于位置，另一个用于交互力，分别沿无约束轴和约束轴。UDT [60]、[78]–[80]和FA [81]车辆都采用了这种控制策略。在[82]中，提出了一种基于优化的直接力控制器。

为了实现之前提出的控制器，需要对状态（在第VII-B节中讨论）和相互作用力进行估计。对于后者，可以使用[32]和[76]中的基于模型的扳手观察者。更直接的解决方案是使用连接到末端执行器的力传感器[70], [82]。这允许在交互控制回路中实现直接反馈。

我们注意到，阻抗/导纳控制器非常容易实现且直观。此外，从非接触式和基于接触的飞行过渡可以通过平滑的增益变化轻松处理。然而，不能保证精确的交互控制。另一方面，混合位置/力控制器可以提供精确的位置和力跟踪，但必须仔细解决接触约束。

D. 物理交互任务

这里，我们对空中机器人社区处理的物理交互任务进行分类。特别是，我们只考虑

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tasks that involve an exchange of forces (or moments) between the environment and the aerial robot.

1) Pick and Place (P&P): The objective is to grasp or release an object not constrained to the environment [36], [75], [83], [84]. The interaction forces play a role only during the P&P operations, which are normally very short in time and can be considered negligible in most of the cases.

2) Point Contact (PC): The objective is to preserve the contact between the environment and the robot end-effector in a single static point. If the end-effector position is constrained, the challenge is to control the intensity and direction of the interaction force [80]. On the other hand, if the end-effector is free to move, the challenges are multiple.

1) Manage the transition from contact-free to contact flight, namely from zero to nonzero interaction forces. Bouncing effects or strong impacts could destabilize or damage the robot.
2) Ensure a sufficient force normal to the interacting surface to guarantee the contact.
3) Keep the interaction force in the friction cone. If this is not ensured, the end-effector might slip causing the crash of the robot. Applications falling into this category are the installation of sensor devices [85], the inspection by contact of tanks [44], pipes [66], and other surfaces [6], [86].

3) Pulling/Pushing (PP): This task is similar to the contact point, but the point of interaction is nonstatic. The interacting surface is not fully constrained and can move in the space along certain directions. When the robot is asked to pull an object, the end-effector position (and perhaps orientation) is in general constrained to the point of interaction. On the other hand, when the robot is asked to push an object, the mechanical constraint between the end-effector and the object is not required as long as the interaction force lays in the friction cone. For PP tasks, the extra challenge w.r.t. point contact is the dynamics of the object that now needs to be considered, together with its kinematic constraints. Classical benchmarks consist of opening/closing a drawer or a door and PP a cart.

4) Sliding (S): The objective is to keep the contact between the end-effector and a static surface, while the end-effector moves on it. The static and dynamic frictions must be considered in the control problem to avoid slippage, ensure the contact, and move the end-effector along the desired trajectory. The most popular application is the continuous contact-based inspection of tanks [44], pipes [66], and other surfaces [87].

5) Peg-in-Hole (PH): the objective is to insert an object (attached to the end-effector) in a hole. If the difference in size between the object and the hole is small, this operation can become very difficult. During the insertion, many of the DoF of the end-effector are constrained. This requires both a precise knowledge of the environment and a suitable impedance shaping to cope with errors and uncertainties that are present in real applications. If impedance shaping is not carefully addressed, high-frequency vibration and resonant effects could lead to instability or damages of the robot.

6) Manipulation (M): Under this last category, we gather all such operations that require the application of specific forces and torques. Examples are the bending of a pipe or a bar, the

TABLE II
MULTIROTOR PLATFORMS FOR PHYSICAL INTERACTION TASKS

Platform	Actuation property	Interac. tool	Task	Reference	Maturity
HL	UDT	GR	P&P	[16], [17]	Exp.
		AA	M	[18]	Exp.
DF	UDT	RL	PC	[64]	Sim.
		AA	PC	[92]	Exp.
ParP	UDT	RL	PC	[93]	Exp.
			S	[76], [94]	Exp.
		GR	P&P	[2]	Exp.
		PL	Transp.	[13], [95]–[97]	Exp.
			P&P	[98]	Exp.
			PC	[79]	Exp.
			M	[99]	Exp.
		AA	see Section III		
TedP	FA	RL	PC	[32], [77]	Exp.
			S	[32]	
			PH		
		PL and GR	P&P	[100], [101]	Exp.
			M		
		AA	PC	[66], [82]	Exp.
			S		
	OA	RL	PC	[102]	Sim.
		AA	S	[44]	Exp.
	OD	RL	push	[81]	Exp.
			S		
			PH		
		GR	P&P	[29]	Exp.
TableP	MDT	PL	PC	[103]	Exp.
	OD and OA	RL	S	[86], [87]	Exp.
M	-	-	P&P	[104], [105]	Exp.
	-	-	PP	[106]	Exp.
MP (DF)	-	RL	PC	[107]	Exp.
MP (ParP)		PL	M	[108]	Exp.
MP (TedP)		PL	M	[109]	Exp.

opening/closing of a valve [88], assembly of structures [89], tree cavity inspection [90], or corrosion repair [91].

According to the specific physical interaction task, aerial platforms are equipped with different tools. The most common are: *rigid link (RL)*, a link rigidly attached to the robot; *gripper (GR)*; *passive links (PL)*, similar to rigid links, but attached to the vehicle by a passive joint (e.g., cables); *Articulated arm (AA)* (see Section III). Some times, the end-effector is made of a soft material, or includes a spring mechanism [6], [44], [66]. This makes the end-effector naturally compliant with the environment from a mechanical point of view.

E. Types of Multirotor Platforms

We finally review all the multirotor platforms that have been employed for physical interaction. We gathered them into clusters sharing similar design characteristics related to the actuation (see Table II). For completeness, we also include helicopters and ducted-fan platforms, which have been investigated in the early state of aerial manipulation. Fig. 2 shows an example for every type of platforms. Exploiting the previous discussion, we also mention the actuation properties, the employed actuation tools, and the targeted tasks.

1) Helicopter (HL): Consists of a main horizontal rotor, providing vertical lift, and a tail rotor mounted vertically to

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涉及环境和空中机器人之间力（或力矩）交换的任务。

1) 拾取和放置（P&P）：目标是抓住或释放不受环境约束的物体[36]、[75]、[83]、[84]。相互作用力仅在P&P运行期间发挥作用，通常时间很短，在大多数情况下可以忽略不计。

2) 点接触（PC）：目标是将环境和机器人末端执行器之间的接触保持在一个静态点上。如果末端效应器的位置受到限制，则挑战在于控制交互作用力的强度和方向[80]。另一方面，如果末端效应器可以自由移动，则挑战是多方面的。

1) 管理从无接触飞行到接触飞行的过渡，即从零作用力到非零作用力。弹跳效应或强烈冲击可能会使机器人不稳定或损坏。
2) 确保有足够的力垂直于相互作用的表面，以保证接触。
3) 将相互作用力保持在摩擦锥中。如果不能确保这一点，末端执行器可能会滑动，导致机器人崩溃。此类应用包括传感器装置的安装[85]、罐[44]、管道[66]和其他表面的接触检查[6]、[86]。

3) 拉/推（PP）：这个任务类似于接触点，但交互点是非静态的。交互曲面没有完全约束，可以在空间中沿特定方向移动。当机器人被要求拉动一个物体时，末端执行器的位置（可能还有方向）通常被限制在交互点。另一方面，当机器人被要求推动一个物体时，只要摩擦力在摩擦锥中，末端执行器和物体之间就不需要机械约束。对于PP任务，w.r.t.点接触的额外挑战是现在需要考虑的对象动力学及其运动学约束。经典的基准测试包括打开/关闭抽屉或门和手推车。

4) 滑动：目标是在末端效应器在其上移动时，保持末端效应器与静态曲面之间的接触。在控制问题中必须考虑静态和动态摩擦，以避免滑动，确保接触，并沿所需轨迹移动末端执行器。最常用的应用是对储罐[44]、管道[66]和其他表面[87]的连续接触式检查。

5) 钉入孔（PH）：目标是在孔中插入对象（连接到末端效应器）。如果物体和孔之间的尺寸差异很小，则此操作可能会变得非常困难。在插入过程中，末端效应器的许多自由度都受到约束。这既需要对环境的精确了解，也需要适当的阻抗成形，以应对实际应用中存在的误差和不确定性。如果不仔细处理阻抗成形，高频振动和共振效应可能会导致机器人不稳定或损坏。

6) 操纵（M）：在最后一类中，我们收集所有需要施加特定力和扭矩的操作。例如，管道或钢筋的弯曲

表II
用于物理交互任务的多转子平台

Platform	Actuation property	Interac. tool	Task	Reference	Maturity
HL	UDT	GR	P&P	[16], [17]	Exp.
		AA	M	[18]	Exp.
DF	UDT	RL	PC	[64]	Sim.
		AA	PC	[92]	Exp.
ParP	UDT	RL	PC	[93]	Exp.
			S	[76], [94]	Exp.
		GR	P&P	[2]	Exp.
		PL	Transp.	[13], [95]–[97]	Exp.
			P&P	[98]	Exp.
			PC	[79]	Exp.
			M	[99]	Exp.
		AA	see Section III		
TedP	FA	RL	PC	[32], [77]	Exp.
			S	[32]	
			PH		
		PL and GR	P&P	[100], [101]	Exp.
			M		
		AA	PC	[66], [82]	Exp.
			S		
	OA	RL	PC	[102]	Sim.
		AA	S	[44]	Exp.
	OD	RL	push	[81]	Exp.
			S		
			PH		
		GR	P&P	[29]	Exp.
TableP	MDT	PL	PC	[103]	Exp.
	OD and OA	RL	S	[86], [87]	Exp.
M	-	-	P&P	[104], [105]	Exp.
	-	-	PP	[106]	Exp.
MP (DF)	-	RL	PC	[107]	Exp.
MP (ParP)		PL	M	[108]	Exp.
MP (TedP)		PL	M	[109]	Exp.

阀门的开启/关闭[88]、结构的组装[89]、树腔检查[90]或腐蚀修复[91]。

根据具体的物理交互任务，空中平台配备了不同的工具。最常见的是：刚性连杆（RL），一种刚性连接到机器人的连杆；夹持器（gr）；被动连杆（pl），类似于刚性连杆，但通过被动接头（如电缆）连接至车辆；铰接臂（AA）（见第三节）。有时，末端执行器由软材料制成，或包括弹簧机构[6]、[44]、[66]。这使得末端效应器从机械角度与环境自然兼容。

E. 多转子平台的类型

最后，我们回顾了所有用于物理交互的多转子平台。我们将它们聚集到具有类似驱动设计特征的集群中（见表二）。为了完整起见，我们还包括直升机和管道风扇平台，它们在空中操纵的早期阶段就已经被调查过。图2显示了每种类型平台的示例。在前面的讨论中，我们还提到了驱动特性、使用的驱动工具和目标任务。

1）直升机（HL）：由一个提供垂直升力的主水平旋翼和一个垂直安装在直升机上的尾桨组成

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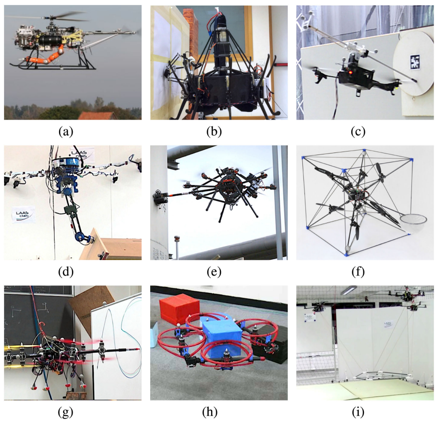

Fig. 2. Representative example for each type of multirotor platforms employed for physical interaction. (a) Helicopter [18]. (b) Ducted-fan [92]. (c) parallel-prop. [93]. (d) Tilted-prop. FA [82]. (e) Tilted-prop. OA [44]. (f) Tilted-prop. OD [29]. (g) Tiltable-prop. OD [86]. (h) Morphing UDT [105]. (i) Multi-platformsys. [108].

counteract the torque from the main rotor. This type of actuation makes HLs UDT. Despite this, HLs were one of the first platforms employed for aerial manipulation. The high payload allowed to equip them with cables for transportation [12], [13], with a gripper for P&P [16], and with industrial robotic arms for manipulation [18], [110]. However, HLs do not seem a really viable option in many applications due to their high complexity and danger during flight close to surfaces. Likely this is the reason why recent works are rather focused on multirotor platforms. In [111], an HL is considered but for the sole objective of holding a cable suspended multirotor aerial manipulator.

2) Ducted Fan (DF): Consists of a main propeller mounted within a cylindrical duct together with some control surfaces. The first creates the total thrust, while the seconds generate moments to control the vehicle attitude. In view of this, it is easy to verify that standard DF platforms are UDT. In [63] a DF equipped with a simple rigid tool has been considered for contact point tasks in a simulation environment. Later, in [92], a real platform equipped with a parallel Delta arm has been experimentally validated for contact point tasks.

3) Parallel Propellers (ParP): Consists of a main rigid frame equipped with multiple propellers fixed to the main frame. Every propeller is directed toward the same direction and typically arranged on the same plane. In the most common cases, they are characterized by four, six, or eight propellers, thus, commonly called *quadrotor*, *hexarotor*, *octorotor*.

In the market, as well as in the state of the art related to aerial physical interaction, this type of platform is the most common. To perform physical interaction tasks, ParP platforms have been equipped with the following:

1) *rigid links*, for point contact [93] and sliding tasks [76], [94];
2) *grippers*, for P&P operations [2];
3) *passive links*, and in particular cables for transportation [13], [95]–[97], P&P [98], point contact [78], [79], and manipulation (assembly) [99];
4) *articulated arms*, for a wide range of tasks, e.g., P&P [112], point contact [113], PP [114], sliding, and manipulation [88]. A complete review is given in Section III.

4) Tilted Propellers (TedP): Consists of a main rigid frame equipped with multiple propellers fixed to it. The propellers are directed toward multiple directions. According to the number, orientation, and type (unidirectional/bidirectional) of propellers, such platforms can be FA, OA, or even OD.

Among the FA platforms, we find the “TiltHex” [55], which has six unidirectional-propellers rigidly attached to the main body, and oriented in different directions. Such a platform has been equipped with the following:

1) a rigid tool for point contact [77], slide, and peg-in hole tasks [32];
2) a passive link together with a gripper for P&P and manipulation tasks [100], [101];
3) an articulated arm for point contact and slide tasks [66], [82].

Among the OA platforms (non OD) we find the “AEROX” [44], which has eight unidirectional-propellers rigidly attached to the main body, and oriented in different directions. This platform has been equipped with an articulated arm for point contact and slide tasks and has been applied for contact inspection of both oil and gas plants and bridges [43]. Among the OD platformss we can find “ODAR” [81], which has eight bidirectional-propellers rigidly attached to the main body, and oriented in different directions. Such a platform has been equipped with a simple rigid tool for tasks like push and slide and peg-in-hole. A platform with a similar propellers configuration is the one in [29]. The platform has been equipped with a pouch for P&P operations and it has been used for the dynamic catching of a thrown ball.

5) Tiltable Propellers (TableP): Consists of a main rigid frame and multiple propellers fixed to movable actuated elements (servo motors). Thanks to the extra actuation, the propellers can be directed toward multiple directions in an independent or coordinated way according to the specific actuation configuration. Several designs have been presented with a different number of tiltable propellers going from 2 to 8, except for 5 and 7. Some of these platform have been proposed in , [30], [56], and [103]. For a detailed survey on platform with TableP, we refer the interested reader to [50]. Although most of the tiltable-propellers platforms are at least FA, there are only few cases in which they are used for physical interaction. In fact, the servo motors are in general not very precise and have a slow dynamics, as well as additional mechanical issues as backlashes.

Papachristos *et al.* [103] proposed a tri-rotor platform in a “T”-like configuration, where the two frontal principal propellers can tilt radially by the same angle, while the tail rotor can tilt independently. Such actuation configuration makes the platform MDT. The platform has been equipped with a passive one-DoF revolute end-effector to accomplish point-contact tasks. Bodie *et al.* [86] and Bodie *et al.* [87] proposed a twelve-rotor platform in a double motor configuration, where each pair of propellers can tilt radially. Such actuation configuration makes the platform

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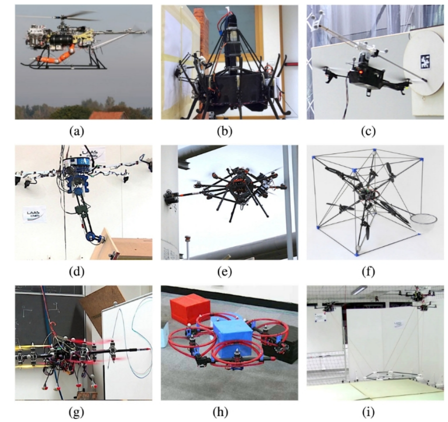

图2. 用于物理交互的每种类型的多转子平台的代表性示例。（a）直升机[18. 。（b）管道风扇[92. 。（c）平行道具。[93. .（d）倾斜的支柱。FA [82. 。（e）倾斜的支柱。OA [44. 。（f）倾斜的支柱。OD [29. 。（g）可倾斜的支柱。OD [86. 。（h）变形UDT [105. 。（i）多平台系统。[108. .

抵消主转子的扭矩。这种类型的驱动会导致HLs UDT。尽管其中一个平台采用了HLs空中操纵。高有效载荷允许它们配备运输电缆[12],[13],P&P夹具[16],以及用于操纵的工业机械臂[18], [110]。然而，在许多应用中，HLs似乎并不是一个真正可行的选择，因为它们在接近地面的飞行过程中具有高度的复杂性和危险性。这可能就是为什么最近的研究主要集中在多转子平台上的原因。在[111]中，考虑了HL，但其唯一目的是固定悬索式多转子空中机械手。

2) 管道风机（DF）：由安装在圆柱形管道内的主螺旋桨和一些控制面组成。第一个产生总推力，而第二个产生控制车辆姿态的力矩。鉴于此，很容易验证标准测向平台是否为UDT。在[63]中，已考虑在模拟环境中为接触点任务配备简单刚性工具的DF。后来，在[92]中，一个装有平行三角臂的真实平台已经在接触点任务中得到了实验验证。

3) 平行螺旋桨（ParP）：由一个主刚性框架组成，该框架配有多个固定在主框架上的螺旋桨。每个螺旋桨都指向同一方向，通常布置在同一平面上。在最常见的情况下，它们的特点是四个、六个或八个螺旋桨，因此，通常称为四旋翼、六旋翼、八旋翼。

在市场上，以及在与空中物理交互相关的最新技术中，这种平台是最常见的。为了执行物理交互任务，ParP平台配备了以下设备:

1) 刚性连杆，用于点接触[93]和滑动任务[76], [94]；
2) 用于P&P操作的夹具[2]；
3) 无源链路，尤其是用于运输[13]、[95]–[97]、P&P [98]、点接触[78]、[79]和操纵（组装）[99]的电缆；
4) 关节臂，用于各种任务，例如P&P [112]、点接触[113]、PP [114]、滑动和操纵[88]。第三节给出了完整的回顾。

4） 倾斜螺旋桨（TedP）：由一个装有多个固定螺旋桨的主刚性框架组成。螺旋桨被导向多个方向。根据螺旋桨的数量、方向和类型（单向/双向），此类平台可以是FA、OA,甚至OD。

在FA平台中，我们发现了“TiltHex” [55],它有六个单向螺旋桨，刚性连接在主体上，朝向不同的方向。这种平台配备了以下设备：:

1) 一种用于点接触、滑动和钉入孔任务的刚性工具[77]；
2) 用于P&P和操作任务[100]、[101]的被动链环和夹持器；
3) 用于点接触和滑动任务的铰接臂[66], [82]。

在OA平台（非OD）中，我们发现了“AEROX” [44],它有八个单向螺旋桨 牢固地附着在主体上，并以不同的方向定位 方向。该平台配备了铰接式平台 手臂用于点接触和滑动任务，并已申请 石油天然气工厂和桥梁的接触检查[43]。 在OD平台中，我们可以找到“ODAR” [81],它有八个固定在主体上的双向螺旋桨，朝向不同的方向。这样的平台配备了一个简单的刚性工具，用于推、滑和钉孔等任务。具有类似螺旋桨配置的平台如[29]所示。该平台配备了一个用于P&P操作的袋，用于动态接球。

5. 可倾斜螺旋桨（TableP）：由一个主刚性框架和多个固定在可移动驱动元件（伺服电机）上的螺旋桨组成。由于额外的驱动,螺旋桨可以根据具体的驱动配置以独立或协调的方式朝向多个方向。除了5. 和7. 螺旋桨外,已经有几种不同数量的可倾斜螺旋桨设计,从2. 到8. 不等。其中一些平台已在[30. 、[56. 和[103. 中提出。有关TableP平台的详细调查,请参阅[50. 。尽管大多数可倾斜螺旋桨平台至少为FA,但它们用于物理交互的情况很少。事实上,伺服电机通常不太精确,动态速度较慢,并且存在额外的机械问题,如反作用力。Papachristos等人[103. 提出了一种“T”形结构的三旋翼平台,其中两个正面主螺旋桨可以以相同的角度径向倾斜,而尾桨可以独立倾斜。这种驱动配置使平台MDT。该平台配备了被动单自由度旋转末端执行器,以完成点接触任务。Bodie等人[86. 和Bodie等人[87. 提出了一种双电机配置的十二转子平台,其中每对螺旋桨都可以径向倾斜。这种驱动配置使平台

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OD and OA. The platform, equipped with a rigid tool has been used for point contact and sliding tasks.

6) Multirotor Morphing (M): Consists of a main body composed by actuated links. Each link, or part of them, is then equipped with one (or multiple) titled- or tiltable-propellers. Thanks to the actuation of the main body links, the robot can not only change the propeller directions, but also their relative positions. Although the mechanical design is even more complex than TableP platforms, morphing ones allow for a very high adaptability to the environment and task needs.

In [115], a quadrotor-like platform with foldable arms has been proposed for simple contactless navigation purposes. For similar tasks, e.g., passing through narrows gaps, a transformable multilinked aerial robot has been presented in [116].

Again, likely due to the mechanical and control complexity of such platforms, M-type aerial systems physically interacting with the environment have been rarely presented. One example of the M-type that has been used for physical interaction is the "HYDRUS" [105]. It consist of a two-dimensional (2-D) multilink structure, where each link is equipped with a propeller. The robot exploits its morphing capability for P&P operations. It can grasp objects of different shapes properly adapting its configuration [104]. An evolution of such a vehicle used for manipulation tasks has been presented in [117] and [106].

7) Multiplatform Systems (MP): consists of multiple multirotor platform (belonging to the previously described types) physically connected forming a new articulated flying platform. Examples of such multirotor based platforms are actuated by: 1) ducted-fans [107] for point contact tasks, 2) parallel-propellers platforms [108] for manipulation tasks, 3) tilted-propellers platforms [109] for manipulation tasks. This particular case of multirobot cooperation for aerial physical interaction is addressed in detail in Section IV.

III. Aerial Platforms With Robotic Arms

A. Morphologies of Aerial Manipulation Robots

The literature review in aerial robotic manipulation reveals a wide diversity of morphologies mainly differing from the designs and implementations of the manipulator, using autonomous HLs [17], [18] and multirotors [20], [83] as aerial platforms. The analysis and comparison of the prototypes according to their kinematic configuration, functionalities, and mechanical construction allows the classification reported in Fig. 3 and Table III.

Possibly because of the widespread use of industrial robotic arms, a significant number of aerial manipulation prototypes employ an upper arm-forearm configuration including shoulder, elbow, and wrist joints, both in the single arm [83], [89], [119], and dual arm [120] case. The number of joints and the kinematic configuration of the arms are determined in principle by the level of dexterity required in the manipulation task, minimizing the number of actuators to reduce the total weight. Redundant and hyper-redundant manipulators [19], [23], [66] are intended to perform tasks requiring the appropriate positioning and orientation of the end-effector when interacting with the objects or the environment. In order to reduce the reaction wrenches induced by the motion of the manipulator, some prototypes employ transmission mechanisms like timing pulleys [118], [119], or

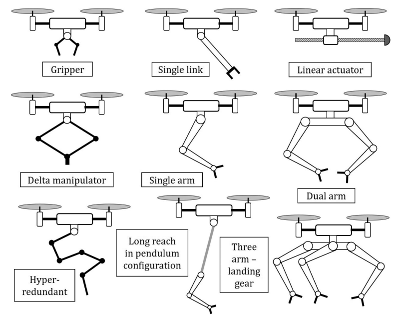

Fig. 3. Different morphologies of aerial manipulation robots.

TABLE III
Different Prototypes of Manipulators, Sorted by Number of DoFs. Types of Platforms Are Multirotor (M) and Helicopter (H). Manipulators Are: Stiff (S), Compliant (C), and Industrial (I)

Morpho.	Ref	Type	DoF	Reach	Weight	Payload
Gripper	[2]	M-C	1	-	-	-
	[16]	H-C	2 × 4	0.39	-	1.5
Single link	[118]	M-C	1	-	-	-
	[87]	M-S	0	-	-	-
	[44]	M-C	1	-	-	-
Linear actuator	[113]	M-C	1	-	-	-
	[85]	M-S	1	0.4	0.48	4.5
Delta manip.	[6]	M-C	3	0.2	0.22	-
	[21]	M-S	3	0.36	0.5	-
	[91]	M-S	3	0.25	0.22	-
Single arm	[83]	M-S	2	0.32	0.37	-
	[20]	M-S	2	-	0.4	0.2
	[66]	M-S	2	-	-	-
	[119]	M-S	5	0.3	0.25	0.2
	[89]	M-S	6	0.45	1.4	-
Multi arm	[88]	M-S	2 × 2	-	-	-
	[36]	M-C	2 × 4	0.5	1.3	0.3
	[120]	M-S	2 × 5	0.5	1.8	0.7
	[35]	M-C	3 × 3	0.37	1.0	-
Hyper-Redundant	[19]	H-I	7	0.88	22	7
	[75]	M-S	7	-	-	-
Long reach	[121]	M-C	2 + 1	1.5	0.8	0.2
	[34]	M-C	8 + 1	1.5	1.6	0.3

rigid bars [120], placing the actuators as close as possible to the base of the aerial platform. The use of parallel mechanisms, as in delta manipulators [6], [21], [91], is useful to reduce the inertia, however, the workspace range is typically much lower compared to a serial manipulator arm. Aerial manipulators with single link [44], [87], [118] and linear actuators [85], [113] have been proposed for tasks involving force interactions with surfaces [93].

The technological limitations of the servo actuators typically employed for building lightweight robotic arms [75], [89], [119], [120], [122], whose capabilities are usually limited to position/velocity control, impede the realization of manipulation tasks involving significant interaction forces. To overcome this problem, the works in [70] and [82] employ a F/T sensor attached at the wrist of a stiff-joint manipulator. Alternatively, in [36],

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OD和OA。该平台配有刚性工具，用于点接触和滑动任务。

6) 多转子变形（M）：由驱动连杆组成的主体组成。然后，每个连杆或其一部分配备一个（或多个）可倾斜螺旋桨。由于主体连杆的驱动，机器人不仅可以改变螺旋桨的方向，还可以改变它们的相对位置。虽然机械设计甚至比TableP平台更复杂，但变形平台允许对环境和任务需求具有非常高的适应性。

在[115]中，提出了一种带有可折叠臂的四旋翼式平台，用于简单的非接触式导航目的。对于类似的任务，例如，通过狭窄的间隙，可变换的多线空中机器人已在[116]中介绍。

同样，由于此类平台的机械和控制复杂性，很少出现与环境进行物理交互的m型天线系统。用于物理交互的m型的一个例子是"HYDRUS" [105]。它由一个二维（2-D）多链路结构组成，每个链路配备一个螺旋桨。 该机器人利用其变形能力进行P&P操作。 它可以通过适当调整其配置来抓取不同形状的物体[104]。[117]和[106]中介绍了用于操纵任务的此类车辆的演变。

7) 多平台系统（MP）：由多个多转子平台（属于前述类型）组成，物理连接形成一个新的铰接式飞行平台。此类基于多转子的平台的示例由以下装置驱动：1）用于点接触任务的导管风扇[107]，2）用于操纵任务的平行螺旋桨平台[108]，3）用于操纵任务的倾斜螺旋桨平台[109]。第四节详细介绍了多机器人合作进行空中物理交互的具体情况。

III. Aerial Platforms With Robotic Arms

A.空中操纵机器人的形态

航空机器人操作方面的文献综述揭示了多种形态，主要不同于机械手的设计和实现，使用自主HLs [17]、[18]和多转子[20]、[83]作为航空平台。根据原型的运动配置、功能和机械结构，对原型进行分析和比较，可以进行图3和表III所示的分类。

可能是由于工业机械臂的广泛使用，大量的空中操纵原型采用上臂-前臂配置，包括单臂[83]、[89]、[119]和双臂[120]的肩关节、肘关节和腕关节。关节的数量和手臂的运动学配置原则上取决于操作任务所需的灵巧程度，从而最小化执行器的数量以减少总重量。冗余和超冗余机械手[19]、[23]、[66]旨在执行与物体或环境交互时需要末端执行器适当定位和定向的任务。为了减少机械手运动引起的反作用扳手，一些原型采用了传动机构，如正时滑轮[118]、[119]或

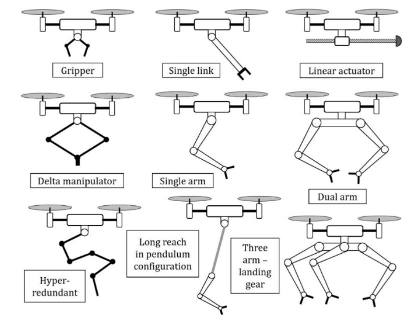

图3. 不同形态的空中操纵机器人。

表III
机械手的不同原型，按自由度排序。平台类型包括多旋翼（M）和直升机（H）。
Manipulators Are: Stiff (S), Compliant (C), and Industrial (I)

Morpho.	Ref	Type	DoF	Reach	Weight	Payload
Gripper	[2]	M-C	1	-	-	-
	[16]	H-C	2 × 4	0.39	-	1.5
Single link	[118]	M-C	1	-	-	-
	[87]	M-S	0	-	-	-
	[44]	M-C	1	-	-	-
Linear actuator	[113]	M-C	1	-	-	-
	[85]	M-S	1	0.4	0.48	4.5
Delta manip.	[6]	M-C	3	0.2	0.22	-
	[21]	M-S	3	0.36	0.5	-
	[91]	M-S	3	0.25	0.22	-
Single arm	[83]	M-S	2	0.32	0.37	-
	[20]	M-S	2	-	0.4	0.2
	[66]	M-S	2	-	-	-
	[119]	M-S	5	0.3	0.25	0.2
	[89]	M-S	6	0.45	1.4	-
Multi arm	[88]	M-S	2 × 2	-	-	-
	[36]	M-C	2 × 4	0.5	1.3	0.3
	[120]	M-S	2 × 5	0.5	1.8	0.7
	[35]	M-C	3 × 3	0.37	1.0	-
Hyper-Redundant	[19]	H-I	7	0.88	22	7
	[75]	M-S	7	-	-	-
Long reach	[121]	M-C	2 + 1	1.5	0.8	0.2
	[34]	M-C	8 + 1	1.5	1.6	0.3

刚性杆[120],将致动器放置在尽可能靠近高空平台底座的位置。在delta机械臂[6]、[21]、[91]中使用并联机构有助于减少惯性，然而，与串联机械臂相比，工作空间范围通常要小得多。对于涉及与表面力相互作用的任务[93]，提出了带有单连杆[44]、[87]、[118]和线性执行器[85]、[113]的航空机械手。

通常用于制造轻型机械臂[75]、[89]、[119]、[120]、[122]的伺服执行器的技术限制，其能力通常限于位置/速度控制，阻碍了涉及显著交互作用力的操纵任务的实现。为了克服这个问题，[70]和[82]中的工作采用了一个固定在刚性关节机械手手腕上的F/T传感器。或者，在[36]中，

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[69], [76], and [123], the estimation and control of the torques acting over the servos is done by measuring the deflection of an elastic element introduced between the actuator and the output link. The works in [85] and [113] exploit the kinetic energy of the aerial platform to apply higher forces, using a linear actuator to regulate the impact force interaction in a passive [113] or active [85] way.

Motivated by the convenience to increase the separation distance between the manipulator and the propellers, the concept of long reach aerial manipulator with dual arm is introduced in [124]. Later, this morphology evolved to the concept of aerial manipulator in pendulum configuration with passive joint at the base [121], [42], increasing safety in the realization of manipulation tasks close to environmental obstacles [34].

B. Compliance

The term compliance in robotic manipulation can be defined as the manipulator ability of accommodating for the forces generated during the physical interactions with the environment or with an agent (human or robot). Intuitively, this concept is associated to an elastic behavior in the joints or links. More formally, the compliance can be formulated as the mechanical impedance (or, analogously, the admittance) that relates the position deviation of the manipulator with the external force, characterized by the inertia, damping, and stiffness. Two forms of compliance can be identified depending on its physical realizations: mechanical [15], [113], [118], [123], [125], or at control/software level [69], [70], [85]. In the first case, an elastic element is introduced in the joints or links of the manipulator, such that a significant deformation is produced when a force within the nominal range of the actuators is exerted. On the other hand, most industrial robotic arms like KUKA, Universal Robots, or ABB, integrate accurate force/torque sensors to control the apparent impedance.

The compliance is a highly desirable feature for an AEROM physically interacting with the environment since the stability of the floating base may be compromised by the forces caused by the dynamic coupling with the manipulator. The ability of accommodating for the motion of the aerial platform [64], [71], [77] and/or the manipulator [69], [76], [113] results very convenient when considering the uncertainties associated to the in-flight operations, especially in outdoor scenarios.

The first works that introduced compliance in aerial manipulation [16], [113], [118], [123], [125] proposed different compliant mechanisms designed for their integration in HLs and multirotors, like grippers [16], lightweight robotic arms [36], [123], linear actuators [113], or flexible joints [118]. Several functionalities were demonstrated, including collision detection and reaction with active-passive compliance [123], [125], generation of high impact forces [113], deflection based torque/force control [69], and safe interaction in contact with the environment [76]. The anthropomorphic, compliant, and lightweight dual arm presented in [36] combines the mechanical compliance with servo protection to improve the robustness, preventing that the actuators are damaged due to impacts or overloads. The modeling and control of compliant joint/arms was extended in [69], proposing a force controller based on Cartesian deflection. The passive joint in the long-reach (pendulum) configurations [34], [42], [121] provides an enhanced capability of accommodation thanks to the fact that no torque is transmitted to the aerial platform about the joint axis, while the force is still exerted along the link direction. In case of impact, the energy absorbed is stored as potential energy in the pendulum, and released later as kinetic energy.

C. Design and Mechatronic Aspects

Although the manipulator should provide a sufficient level of dexterity to accomplish the task, increasing the number of joints of the manipulator introduces some problems. The most evident is the reduction in the payload capacity and flight time of the aerial platform. This can be clearly identified expressing the mass distribution of the AEROM as $m_{\mathrm{AP}} + m_M + PL_M <= \eta$MTOW, where m_{AP} is the weight of the aerial platform (including all its components except the manipulator), m_M and PL_M are the weight and payload capacity of the manipulator, MTOW is the maximum take-off weight, and η is the load index of the platform. Different approaches can be adopted in the design of the robot depending on how this equation is interpreted.

1) Design determined by the weight of the payload (PL_M): some works propose the use of aerial robots in tasks involving the grasping [36], [83], [84], installation [85], or interaction [44], [66] with devices whose weight is predefined.
2) Design determined by the level of dexterity (m_M): the number of joints is designed to obtain the manipulation dexterity required to accomplish the task. It is possible to distinguish between manipulators that use the joints for end-effector positioning [20], [35], [66], [83] or orientation [19], [119]. Insertion [110] and assembly operations [89] are examples where joints for orienting the wrist are required.
3) Design determined by the available payload (MTOW): if the user or application demand the use of a particular aerial platform, then the weight of the on-board systems (m_{AP} and m_M) and the payload capacity (PL_M) are constrained by ηMTOW. For example, safety reasons may impose a maximum total weight or maximum size of the AEROM.

Metrics like the lift load capacity or the payload-to-weight ratio are useful for evaluation and comparison purposes [48]. The so called smart servos like Dynamixel [35], [83], [88], [89], [91] or Herkulex [36], [120] are currently the best option for building lightweight robotic arms for aerial manipulation. These devices integrate the motor, gearbox, electronics, and communications in a compact device with a relatively high torque-to-weight ratio. These features significantly simplify the design and development tasks, although their performance is limited to position control at low update rates, usually below 100 [Hz]. Some models allow the open-loop torque control, acting directly over the current signal. However, the friction of the gearbox makes impossible to estimate or control accurately the torque at the output link.

D. Single Arm Versus Dual Arm

Most of the aerial manipulation prototypes developed in the last decade consider a single manipulator attached to the aerial

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[69]、[76]和[123],通过测量致动器和输出连杆之间引入的弹性元件的挠度，对作用在伺服装置上的扭矩进行估计和控制。[85]和[113]中的工作利用高空平台的动能施加更大的力，使用线性致动器以被动[113]或主动[85]的方式调节冲击力相互作用。

为了方便增加机械手和螺旋桨之间的分离距离，在[124]中引入了双臂长距离空中机械手的概念。后来，这种形态演变为摆锤配置的空中机械手的概念，基座上有被动关节[121], [42],增加了在接近环境障碍物的情况下执行操纵任务的安全性[34]。

B. 合规性

机器人操作中的顺应性一词可以定义为机械手适应与环境或代理（人类或机器人）物理交互过程中产生的力的能力。直觉上，这个概念与关节或链接中的弹性行为有关。更正式地说，柔度可以表示为机械阻抗（或类似的导纳），它将机械手的位置偏差与外力联系起来，以惯性、阻尼和刚度为特征。根据其物理实现，可以确定两种形式的合规性：机械[15]、[113]、[118]、[123]、[125]或控制/软件级别[69]、[70]、[85]。在第一种情况下，在机械手的关节或连杆中引入一个弹性元件，以便在施加致动器标称范围内的力时产生显著变形。另一方面，大多数工业机械臂，如KUKA、Universal Robots或ABB,都集成了精确的力/扭矩传感器来控制视在阻抗。

合规性是AEROM非常理想的特性
由于浮动基座的稳定性可能会受到机械手动态耦合产生的力的影响，因此与环境进行物理交互。当考虑到与飞行操作相关的不确定性时，特别是在室外场景中，适应空中平台[64]、[71]、[77]和/或操纵器[69]、[76]、[113]运动的能力非常方便。

第一批引入空中操纵合规性的工作[16]、[113]、[118]、[123]、[125]提出了不同的合规机制，设计用于HLs和多转子的集成，如夹具[16]、轻型机械臂[36]、[123]、线性执行器[113]或柔性关节[118]。演示了几种功能，包括碰撞检测和主动被动合规反应[123]、[125]、产生高冲击力[113]、基于偏转的扭矩/力控制[69]以及与环境接触时的安全交互[76]。[36]中介绍的拟人、柔顺和轻质双臂结合了机械柔顺性和伺服保护，以提高鲁棒性，防止执行器因碰撞或过载而损坏。[69]扩展了柔顺关节/手臂的建模和控制，提出了一种基于笛卡尔挠度的力控制器。长距离（摆锤）配置中的被动关节[34], [42], [121]提供了更高的适应能力，这是因为当力仍然沿着连杆方向施加时，没有扭矩围绕关节轴传递到空中平台。在发生碰撞的情况下，吸收的能量作为势能存储在摆锤中，然后作为动能释放。

C. 设计和机电方面

尽管机械手应该提供足够的灵活性来完成任务，但增加机械手的关节数量会带来一些问题。最明显的是空中平台有效载荷能力和飞行时间的减少。这可以清楚地确定，表达了
AEROM的质量分布为$m_{AP} + m_M + PL_M <= \eta$MTOW,其中$m_{AP}$是高空平台（包括除机械手以外的所有部件）、$m_M$和$PL_M$的重量
是机械手的重量和有效载荷能力，MTOW是最大起飞重量，η是平台的负载指数。在机器人的设计中，可以采用不同的方法，这取决于这个方程的解释方式。

1) 由有效载荷的重量决定的设计（PL_M）：一些工作建议在任务中使用空中机器人，包括抓取[36]、[83]、[84]、安装[85]或与重量预定义的设备交互[44]、[66]。
2) 由灵巧程度（m_M）决定的设计：
关节数量旨在获得完成任务所需的操作灵活性。可以区分使用关节进行末端执行器定位的操纵器[20]、[35]、[66]、[83]或ori-
内倾[19], [119]。插入[110]和装配操作[89]都是需要关节定位手腕的例子。
3) 由可用有效载荷（MTOW）确定的设计：如果用户或应用程序要求使用特定的空中平台，则车载系统（m_{AP}和m_M）的重量和有效载荷容量（PL_M）受ηMTOW的限制。例如，出于安全原因，AEROM可能会施加最大重量。

提升载荷能力或有效载荷重量比等指标对于评估和比较非常有用[48]。Dynamixel [35]、[83]、[88]、[89]、[91]或Herkulex [36]、[120]等所谓的智能伺服系统目前是制造用于空中操纵的轻型机械臂的最佳选择。这些设备将电机、齿轮箱、电子设备和通信集成在一个紧凑的设备中，具有相对较高的扭矩重量比。这些特性极大地简化了设计和开发任务，尽管它们的性能很低
仅限于低更新率下的位置控制，通常低于100 [Hz]。一些型号允许开环扭矩控制，直接作用于电流信号。然而，齿轮箱的摩擦力使得无法准确估计或控制输出连杆处的扭矩。

D. 单臂与双臂

过去十年中开发的大多数空中操纵原型都考虑将一个操纵器连接到空中

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platform, and only a few of them explore the use of two [36], [68], [88], [120] or three [35] arms. By using identical arms, the integration on the platform is simplified and shoulder-like mechanical interfaces can be used to interconnect the arms with the platform, as in [36] and [120].

The dexterity and manipulation capabilities of a dual arm system allow the realization of tasks that cannot be accomplished with a single manipulator. The grasping and manipulation of long objects like bars or tubes [42] is a clear example where a dual arm manipulator results more convenient than a single arm. Other examples are: valve turning [88], cooperative bimanual grasping, and some assembly operations [89]. A multiarm system increases the payload capacity, extends the effective workspace of the aerial manipulator [120], [121], and allows the partial cancellation of the reaction wrenches induced by one arm over the aerial platform using the other arm as reaction [120]. The development of human-size [120] and human-like [36] dual arms is also motivated by the convenience to replicate the abilities of human operators.

One capability of a dual arm aerial manipulator that results especially interesting is the use of one arm as position sensor relative to a grabbing point while the other arm conducts the manipulation task. The idea is to estimate the position of the aerial platform relative to the grabbing point from the information provided by the joint servos. It is necessary to remark that the positioning accuracy of the aerial platform should be below the 10% of the reach of the manipulator to ensure that the aerial manipulation task can be accomplished in a reliable way [48]. This problem is very relevant in outdoors applications, as the accuracy of position estimation systems like RTK-GPS may not be good enough.

E. Control

The functionalities and potential applications of an AEROM are determined by the control capabilities of the aerial platform and the manipulator, considered as a whole. In the following, we revise specific motion controllers for aerial manipulators based on the dynamic model [43].

1) *Decoupled:* These methods consider the aerial vehicle and the robotic arm as two subsystems that are controlled independently [65], [70], [122]. The decoupled approach relies on the assumption that the influence of the manipulator over the attitude and position dynamics of the aerial platform is relatively small. The dynamic coupling is neglected or at best treated as a disturbance to compensate [19]. This motivates the design of low weight and low inertia manipulators [119], [120]. Decoupled control methods best perform only in quasi-static motions. As soon as the motion is more demanding in terms of accelerations, these methods fail, or in the best case show large tracking errors.
2) *Coupled:* These methods consider the system as a unique entity. The design of a coupled control scheme relies on the full dynamic model, which explicitly takes into account the dynamic coupling through the inertia matrix [120]. Therefore, this approach is more suited for dynamic cases and allow better performance in terms of position accuracy and stability. Coupled controllers proposed in the state of the art are strongly model-based and consider the full dynamics of the system [58], [61], [126]. A complete overview of such control methods is available in [52]. Furthermore, it requires the real-time computation of the dynamic model of a system with $6 + NM$ DoFs, being N the number of arms and M the number of joints per arm. They often require torque controlled motors that are in general unfeasible for aerial manipulators built with conventional servo actuators.
3) *Partially coupled:* The control of the aerial platform and the manipulator are independent, but the controllers exploit the information provided by each of the systems to estimate the interaction wrenches and improve the performance of the compound, typically in terms of positioning accuracy [75], [83]. To this category belongs the multi-layer architecture presented in [122], where a momentum-based observer [71] is employed to compensate the dynamic couplings, and the variable parameter integral backstepping controller in [20].
4) *Decoupled flatness based:* This approach is in between decoupled and coupled approaches. Each DoFs is controlled independently, as in a decoupled controller, but the full system dynamics is considered via a feed-forward term computed thanks to the differential flatness property of some aerial manipulators [127].

F. Design and Application Guidelines

Given the wide variety of prototypes that can be found in the literature, it is convenient to formulate a design methodology to facilitate the development of specific solutions to particular applications. Autonomous HLs are in general more suited for the manipulation of heavy loads and high operation times. Fully actuated multirotors equipped with few DOF's manipulators are suitable for exerting contact forces on surfaces like walls or tanks, whereas dexterous robotic arms are more appropriate when the application requires the adequate full-pose control of the end-effector. Delta manipulators have been employed due to their compact design and low inertia, that favors the accurate position control. Dual arm and three-arm systems have been proposed to conduct bimanual manipulation tasks where a single arm may not be appropriate, introducing the long reach configuration to improve safety by reducing the probability of collision.

The design and development of an aerial manipulation robot requires the choice of the specific components or modules required to accomplish the task in the most effective and reliable way, rather than developing a general purpose aerial robot. Some features like accurate position estimation and control or compliant interaction control are usual requirements in a wide variety of applications. The positioning accuracy is probably one of the most challenging requirements in outdoor scenarios. Nevertheless, the operation time and payload capacity of the aerial platform, which are directly related to its size and weight, are currently the two main limiting factors in practice. The use of big platforms (> 25 [kg] weight) should be avoided due to the inconveniences associated to its deployment and operation, safety, regulation, maintenance, and repair.

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他们中只有少数人探索使用两个[36]、[68]、[88]、[120]或三个[35]臂。通过使用相同的臂，简化了平台上的集成，并且可以使用肩状机械接口将臂与平台互连，如[36]和[120]所示。

双臂系统的灵巧性和操纵能力允许实现单操纵器无法完成的任务。抓取和操纵杆或管等长物体[42]是一个明显的例子，双臂机械手比单臂更方便。其他例子还有：阀门转动[88]、合作双手抓取和一些装配操作[89]。多臂系统增加了有效载荷容量，扩展了空中操纵器的有效工作空间[120], [121],并允许使用另一个臂作为反作用[120]部分取消一个臂在空中平台上引起的反作用扳手。人类尺寸[120]和类人[36]双臂的发展也是出于复制人类操作员能力的便利性。

双臂空中机械手的一个特别有趣的功能是使用一只手臂作为相对于抓取点的位置传感器，而另一只手臂执行操作任务。其想法是根据联合伺服系统提供的信息，估计空中平台相对于抓取点的位置。需要注意的是，高空作业平台的定位精度应低于机械手可触及范围的10%，以确保高空作业
操作任务可以可靠地完成[48]。
这个问题在户外应用中非常重要，因为RTK-GPS等位置估计系统的精度可能不够高。

E.控制

AEROM的功能和潜在应用取决于空中平台和机械手的控制能力，将其视为一个整体。在下文中，我们基于动力学模型修改了航空机械手的特定运动控制器[43]。

1) 解耦：这些方法将飞行器和机械臂视为独立控制的两个子系统[65]、[70]、[122]。解耦方法基于机械手对空中平台姿态和位置动力学的影响相对较小的假设。动态耦合被忽略，或充其量被视为一种干扰进行补偿[19]。这推动了低重量、低惯性机械手的设计[119], [120]。解耦控制方法仅在准静态运动中表现最佳。一旦运动在加速度方面要求更高，这些方法就会失败，或者在最好的情况下显示出较大的跟踪误差。
2) 耦合：这些方法将系统视为一个独特的实体。耦合控制方案的设计依赖于全动态模型，该模型通过惯性矩阵明确考虑了动态耦合[120]。因此，这种方法更适合动态情况，并在位置精度和稳定性方面具有更好的性能。该州提出的耦合控制器现有技术中的大多数都是基于模型的，并考虑了系统的全部动态[58]、[61]、[126]。[52]中提供了此类控制方法的完整概述。此外，它需要实时计算6+NM自由度系统的动力学模型，即N个臂的数量，M个臂的关节数量。它们通常需要扭矩控制的电机，而这些电机通常不适用于使用传统伺服执行器制造的航空机械手。
3) 部分耦合：空中平台和机械手的控制是独立的，但控制器利用每个系统提供的信息来估计交互扳手，并改善化合物的性能，通常是在定位精度方面[75], [83]。属于这一类的是[122]中介绍的多层体系结构，其中使用基于动量的观测器[71]来补偿动态耦合，以及[20]中的可变参数积分反推控制器。
4) 基于解耦平面度：该方法介于解耦和耦合方法之间。每个自由度都是独立控制的，就像在解耦控制器中一样，但全系统动力学是通过前馈项来考虑的，这是由于一些航空机械手的微分平坦性[127]。

F.设计和应用指南

鉴于文献中可以找到各种各样的原型，制定一种设计方法来促进针对特定应用开发特定解决方案是很方便的。自动HLs通常更适合于重负载和高运行时间的操作。配备少自由度机械手的全驱动多转子适合在墙壁或坦克等表面上施加接触力，而当应用需要对末端执行器进行充分的全姿态控制时，灵巧的机械臂更合适。Delta机械手由于其紧凑的设计和低惯性而被采用，这有利于精确的位置控制。在单臂可能不合适的情况下，建议使用双臂和三臂系统执行双手操作任务，引入长距离配置，通过降低碰撞概率来提高安全性。

一种空中操纵机器人的设计与开发
需要选择以最有效和可靠的方式完成任务所需的特定组件或模块，而不是开发通用航空机器人。精确的位置估计和控制或兼容的交互控制等功能是各种应用中的常见要求。定位精度可能是户外场景中最具挑战性的要求之一。然而，空中平台的运行时间和有效载荷容量与其尺寸和重量直接相关，是目前实践中的两个主要限制因素。由于部署和操作、安全、监管、维护和维修方面的不便，应避免使用大型平台（> 25 [kg]）。

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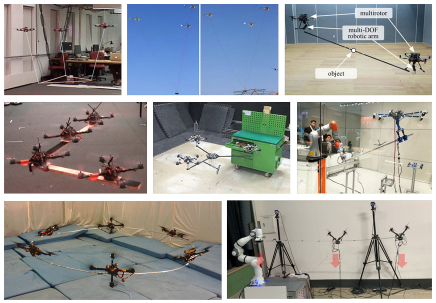

Fig. 4. Examples of aerial cooperative manipulation systems (from top, from left): 1) multiquadrotor cable-suspended transport [7]; 2) multihelicopter cable-suspended transport [12]; 3) cooperative aerial manipulators [128]; 4) rigidly-attached quadrotors [129]; 5) SmQ platform [130]; 6) MAGMaS platform [101]; 7) flexible ring cooperative manipulation [131]; and 8) distributed vibration suppression with RVMs [132].

IV. Cooperative Aerial Manipulation

To handle an object too heavy or too large for a single aerial robot, the concept of cooperative manipulation has been investigated. A team of multiple aerial robots is deployed to transport and manipulate a common object while increasing the total payload or the moment arm length via their cooperation. In this section, we survey some representative works in the area of cooperative aerial manipulation.

One of the earliest successful demonstrations for this aerial cooperative manipulation is the cable-suspended transportation and manipulation by multiple quadrotors or HLs (e.g., [7]–[10], [12], [13], [108]). Michael *et al.* [7], [9] considered the problem of cooperative transportation of a triangular plate-like payload by three quadrotors with a cable connected between each of their center-of-mass and a point on the payload (see Fig. 4). The key idea of [7] was to convert the problem as a quasi-static motion planning problem, i.e., given each waypoint of the desired payload pose in SE(3), compute the position of each quadrotor, which optimizes certain measures (e.g., Hessian of the payload pose) while satisfying certain feasibility conditions (e.g., positive cable tension, collision avoidance). However, the results of [7] suffer from the multiple solutions of the forward kinematics, i.e., given the quadrotors' position, the payload can subsume 3-DoFs motion relative to the quadrotors. This issue was then resolved in [9] by enforcing so called "cone-constraint" of each quadrotor's position relative to the payload pose and other quadrotors' positions.

All the works in [7], [9], and [108] are yet kinematic results, thus, not able to realize high-speed dynamic payload transport with the quadrotor-payload dynamic coupling. This limitation was then addressed in [133] by formulating the quadrotor-payload system as a differentially-flat hybrid system (with the system of positive tension defining a differentially-flat subsystem and switching to other subsystem with the cable slack) and planning a dynamically-feasible trajectory for that. This dynamic cable-suspended transportation was also demonstrated using three small-size HLs in [12] and [13], where a 2-DoFs cable angle sensor and a cable-tension sensor were installed to measure and compensate for the cable tension on the HL dynamics, an approach more suitable for large-size aerial robots with enough load-carrying capacity (see Fig. 4). In total, two-quadrotor distributed cable-suspended manipulation of a rod payload with only on-board sensors (i.e., monocular camera and IMU) was demonstrated in [134] with some simplifying assumptions (i.e., two decoupled slung-load systems, no cable slack, straight trajectory, etc.) and also in [72], [73], and [135] based on the leader-follower setting with the use of an admittance control together with a wrench observer.

Aiming for more precise pose control of the payload, the idea of deploying multiple aerial manipulators (i.e., quadrotor with a multi-DoFs arm - see Section III) has been explored [128], [136]–[139]. One of the key challenges for this is the complicated and high-dimensional dynamics of the total system, which is further exacerbated by the interaction with the environments/objects (e.g., unilateral grasping). Yang *et al.* [136] solved this dynamics and presented a hierarchical control law when the multiple aerial manipulators grasp and manipulate a common rigid object via friction-cone contact constraint. Whereas, Yang and Lee [137] circumvented this dynamics complexity by utilizing two impedance control-loops (i.e., object-level control and internal force regulation) with the rigid object grip assumption. Both of these works [136], [137] were validated only with simulations though.

Kim *et al.* [128], Lee *et al.* [138], and Kim *et al.* [139] presented frameworks for the cooperative manipulation of a rod-like object by using two aerial manipulators and their experimental demonstrations (see Fig. 4). In [138], an adaptive sliding-mode control was presented to estimate and reject disturbances including the object's dynamics with the rigid-grip and equal object weight distribution assumptions. A RRT*-based path planning method was also devised to drive the object. The results of [138] were extended in [139] to incorporate obstacle avoidance, and the technique of rapidly-exploring random tree (RRT)*-parametric dynamic movement primitives (PDMPs) was proposed, where the RRT* was used for learning the motion parameters given the obstacle information in the form of dynamic movements primitives for fast and robust path planning. A null-space-based (NSB) control scheme was proposed in [128], where an inner-loop control was designed to robustly control each hexarotor while estimating and rejecting disturbances including their own arm dynamics, whereas the outer-loop control computed reference velocity for the system while incorporating internal force regulation and collision avoidance in an NSB hierarchy.

Another line of research for cooperative manipulation is to directly or rigidly attach multiple quadrotors on an object and use them as distributed actuators to transport and manipulate that object, thereby, overcoming the limitations of a single aerial robot while retaining mechanical simplicity. This idea was first demonstrated in [129], where four quadrotors were rigidly attached on a planar rigid payload of various shapes (e.g., L-shape, T-shape) with their thrust directions all normal to the payload surface. A two-norm optimal control was also derived and partially decentralized in [129] for scalability along with a special microspine mechanism to quickly grip the payload. The

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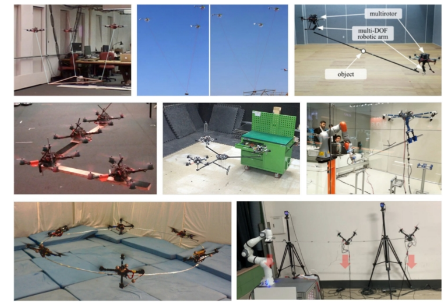

图4. 空中协同操纵系统示例（从上到左）：1. 多四旋翼缆索悬挂运输[7. ；2. 多直升机缆索悬挂运输[12. ；3. 合作式空中机械手[128. ；4. 刚性连接的四转子[129. ；5. SmQ平台[130. ；6. 岩浆台地[101. ；7）柔性环协同操作[131]；8）RVMs的分布式振动抑制[132]。

IV. Cooperative Aerial Manipulation

为了处理单个空中机器人无法处理的过重或过大物体，研究了协同操作的概念。一个由多个空中机器人组成的团队被部署来运输和操纵一个共同的物体，同时通过他们的合作增加总载荷或力矩臂长度。在本节中，我们将介绍一些合作空中操纵领域的代表性作品。

这种空中协同操纵的最早成功演示之一是多个四旋翼机或HLs（例如[7]–[10]、[12]、[13]、[108]）的悬索运输和操纵。Michael等人[7], [9]考虑了三个四转子协同运输三角形板状有效载荷的问题，每个四转子的质心和有效载荷上的一个点之间连接有一根电缆（见图4）。[7]的关键思想是将问题转化为准静态运动规划问题，即，给定se（3）中所需有效载荷姿态的每个航路点，计算每个四旋翼的位置，从而优化某些措施（例如有效载荷姿态的Hessian），同时满足某些可行性条件（例如，正缆绳张力、防撞）。然而，[7]的结果受到正向运动学的多个解的影响，即给定四旋翼的位置，有效载荷可以包含相对于四旋翼的3自由度运动。在[9]中，通过对每个四旋翼相对于有效载荷姿态和其他四旋翼位置的位置实施所谓的"锥形约束"，解决了这个问题。

[7]、[9]和[108]中的所有工作都是运动学结果，
因此，无法通过四转子有效载荷动态耦合实现高速动态有效载荷传输。在[133]中，通过将四旋翼-有效载荷系统描述为一个差平混合系统（正张力系统定义了一个差平子系统，并切换到另一个有电缆松弛的子系统），以及为此规划一个动态可行的轨迹，解决了这一限制。还演示了这种动态缆索悬挂运输使用[12]和[13]中的三个小型HL，其中安装了一个2自由度的电缆角度传感器和一个电缆张力传感器，以测量和补偿HL动力学上的电缆张力，这是一种更适合具有足够承载能力的大型空中机器人的方法（见图4）。总之，在[134]和[72]、[73]中，通过一些简化的假设（即两个解耦的悬挂负载系统、无电缆松弛、直线轨道等），证明了仅使用车载传感器（即单目摄像头和IMU）的杆式有效载荷的双四旋翼分布式电缆悬挂操纵，[135]基于导-从设置，使用导纳控制和扳手观测器。

为了对有效载荷进行更精确的姿态控制，已经探索了部署多个空中操纵器（即，带多自由度臂的四旋翼机，见第三节）的想法[128]、[136]–[139]。这方面的关键挑战之一是整个系统的复杂和高维动力学，与环境/物体的相互作用（例如，单边抓取）进一步加剧了这一问题。Yang等人[136]解决了这一动力学问题，并提出了多个空中机械手通过摩擦锥接触约束抓取和操纵一个普通刚性物体时的分层控制律。然而，Yang和Lee [137]利用两个阻抗控制回路（即物体水平控制和内力调节）和刚性物体抓地力假设，规避了这种动力学复杂性。然而，这两项工作[136]、[137]仅通过模拟进行了验证。

Kim等人[128]、Lee等人[138]和Kim等人[139]
介绍了使用两个空中操纵器对杆状物体进行协同操纵的框架及其实验演示（见图4）。在[138]中，提出了一种自适应滑模控制，以估计和抑制干扰，包括在刚性抓地力和等对象重量分布假设下的对象动力学。还设计了一种基于RRT的路径规划方法来驱动目标。[138]的结果在[139]中进行了扩展，以纳入避障，并提出了快速探索随机树（RRT）-参数化动态运动原语（PDMPs）的技术，其中RRT用于学习以动态运动原语形式给出障碍物信息的运动参数，以实现快速、稳健的路径规划。[128]中提出了一种基于零空间（NSB）的控制方案，其中内环控制被设计为鲁棒控制每个六旋翼，同时估计和抑制干扰，包括其自身的手臂动力学，而外环控制计算系统的参考速度，同时将内力调节和碰撞避免纳入NSB层次结构。

合作操纵的另一个研究方向是
直接或刚性地将多个四旋翼连接到一个物体上，并将其用作分布式执行器来运输和操纵该物体，从而克服了单个空中机器人的局限性，同时保持了机械简单性。这一想法首次在[129]中得到证明，其中四个四旋翼刚性连接在各种形状（如l形、t形）的平面刚性有效载荷上，其推力方向均垂直于有效载荷表面。[129]中还推导了一个双范数最优控制，并将其部分分散，以实现可扩展性，以及一种特殊的微卫星机制，用于快速抓取有效载荷。这个

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result of [129] was extended in [140], where two quadrotors were used to transport a rigid rod only with on-board sensing (i.e., monocular camera and IMU) based on a nonlinear controller capable of more agile maneuvers.

The results of [129], [140] are more for transportation than for manipulation, as it is not possible to control the position and orientation of the object independently due to the well-known underactuation property of the multirotors (with all the rotors parallel with each other). To overcome this issue of underactuation, the spherically-connected multiquadrotor (SmQ) system was proposed in [130] and [141], where multiple quadrotors were attached to a platform via spherical joints to render the platform fully-actuated (e.g., can maintain attitude during side-way motion) - see Fig. 4. A dynamics-based control law, which also addressed the rotating limit of the spherical joints via constrained optimization, was designed and validated with various experimental demonstrations for the SmQ platform in [130]. This spherical joint connection, which allows for omni-direciontal thrust generation, was adopted in [135] as well. Similarly in [142] (see Section VI).

In addition to purely aerial cooperative manipulation systems as discussed so far, there are recently emerging results on the mixed deployment of aerial and ground robots to exploit their complementary capabilities, that are: the ground robots often possess high load carrying ability, yet, with limited workspace, whereas the aerial robots possess unlimited workspace (and ability to easily increase moment-arm length), yet, with limited payload. Mohammadi *et al.* [142] presented a cooperative manipulation system consisting of a ground mobile robot and a quadrotor, where the position of a rigid object was controlled by the mobile robot while its tilting angle by the (spherically connected) quadrotor. However, the result of [143] is limited only for the sagittal plane similar to the case of a two-DoFs pendulum-cart system. On the other hand, the multiple aerial ground manipulator system (MAGMaS) was proposed in [144], where a seven-DoFs KUKA LBR iiwa industrial manipulator and a (spherically connected) quadrotor were controlled to cooperatively manipulate a long rigid object, which was too heavy and too long to be individually handled by either robots (see Fig. 4). This MAGMaS system was then extended in [101] with the spherical joint replaced by the OTHEX system [100] for higher and wider-angle thrust capacity with the bilateral teleoperation ability also added; and further expanded in [145], where the flexibility of the object, likely arising for long-slender or large-size/thin objects, was incorporated. The authors designed a control law for the cooperative manipulation of the flexible object while suppressing its vibration, proving its controllability as well.

The area of aerial cooperative manipulation of flexible or soft objects has not been investigated much so far. Nguyen *et al.* [130] considered the problem of cooperative handling a flexible ring by six quadrotors, each rigidly attached to the ring with some tilted angle to directly provide horizontal-direction control force (see Fig. 4). The dynamics model of the ring with each quadrotor as wrench generator was linearized about the hovering configuration and Kalman estimation and linear quadratic regulator were applied to regulate the ring pose while suppressing its vibration modes. Vibration control of a long flexible beam of skewed rectangular cross section with distributed rotor-based vibration suppression modules (RVMs) was investigated recently in [132], where the two-rotor modules, whose design was optimized to maximize thrust force generation in the longitudinal-vertical plane with minimal torsional torque, were distributed along the beam. Furthermore, optimal placement problem was solved by maximizing controllability Gramian and the vibration suppression was experimentally demonstrated (see Fig. 4).

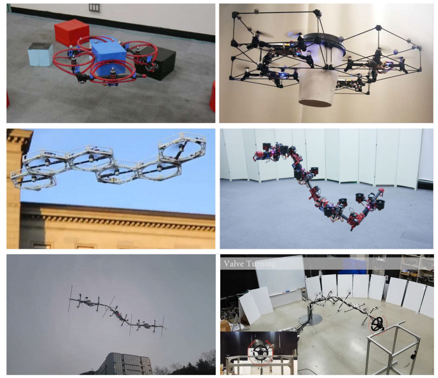

Fig. 5. Examples of interconnected actuated multibody designs (from top, from left): 1) HYDRUS [105]; 2) flying-gripper [146]; 3) DFA [147]; 4) DRAGON [148]; 5) flying LASDRA [149]; and 6) operation LASDRA [109].

V. Interconnected Actuated Multibody Designs

This section surveys a recently emerging class of aerial robotic platforms, which consist of multiple articulated links or bodies, that are mechanically connected with each other via passive or actuated joints and fly with tilted or tilting rotors distributed over them. This kind of platforms can fly while changing their shape, thereby, can realize novel scenarios as follows:

1) aerial grasping of objects by directly using their bodies;
2) aerial operation in cluttered environment via serpentine motion;
3) very large-size robots, that can do aerial manipulation free from classical issues as short operation time, low payload, difficulty in control and sensing;
4) articulated flying characters in amusement parks.

Anzai *et al.* [104], Park *et al.* [149], and Shi *et al.* [150] presented the horizontally deformable aerial robot with two-dimensional mUltilinkS (HYDRUS) (transformable multirotor with 2-D multilinks) platform. Each link module consists of one rotor with enclosing cage and one servo-motor with its rotation axis parallel to the one of the rotor. Thereby, the robot can change its shape in the horizontal plane while retaining the hovering efficiency of typical multirotors. The platform also demonstrated whole-body aerial gripping and transport of a box-like object considering friction cone constraints, and the rotor and servo-motor actuation limitations (see Fig. 5). This HYDRUS platform was also used in [152] to transport multiple

这篇文章已被接受收录在本刊未来的一期中。除分页外，内容均为最终内容。

[129]的结果在[140]中得到了扩展，在[140]中，两个四旋翼仅用于运输刚性杆，并基于能够进行更灵活机动的非线性控制器进行车载传感（即单目摄像头和IMU）。

[129. 、[140. 的结果更多地用于运输而非操作，因为由于多转子（所有转子相互平行）的欠驱动特性，不可能独立控制物体的位置和方向。为了克服欠驱动问题，在[130. 和[141. 中提出了球形连接的多四转子（SmQ）系统，其中多个四转子通过球形接头连接到平台上，以使平台完全驱动（例如，可以在侧向运动期间保持姿态），见图4. 此外，还通过SmQ试验平台验证了基于SmQ的各种旋转极限控制。[135. 中也采用了这种允许产生全方向推力的球形接头连接。类似于[142. （见第六节）。

除了纯粹的空中协同操纵系统

正如到目前为止所讨论的，最近出现了关于混合部署空中和地面机器人以利用其互补能力的结果，即：地面机器人通常具有较高的承载能力，但工作空间有限，而空中机器人具有无限的工作空间（以及轻松增加力矩臂长度的能力），但有效载荷有限。Mohammadi等人[142]提出了一种由地面移动机器人和四旋翼组成的协同操纵系统，其中刚性物体的位置由移动机器人控制，而其倾斜角度由（球形连接的）四旋翼控制。然而，[143]的结果仅限于矢状面，类似于双自由度摆车系统的情况。另一方面，在[144]中提出了多空中地面机械手系统（MAGMaS），其中一个七自由度的KUKA LBR iiwa工业机械手和一个（球形连接的）四旋翼被控制来协同操作一个长刚性物体，该物体太重太长，无法由任何一个机器人单独操作（见图4）。然后，该岩浆系统在[101]中进行了扩展，球形接头被OTHEX系统[100]取代，以获得更高、更宽的角度推力能力，同时还增加了双边远程操作能力；并在[145]中进一步扩展，其中纳入了物体的柔韧性，可能出现在细长或大尺寸/薄物体上。作者设计了一种控制律，用于在抑制柔性物体振动的同时对其进行协同操纵，并证明了其可控性。

空中协同操纵柔性或柔性机器人的领域

到目前为止，对物体的研究还不多。Nguyen等人[130]考虑了六个四转子协同处理柔性环的问题，每个四转子以一定的倾斜角度刚性连接到环上，以直接提供水平方向控制力（见图4）。将每个四转子作为扳手发生器的环的动力学模型线性化为悬停构型，并采用卡尔曼估计和线性二次调节器来调节环的姿态，同时抑制其振动模式。基于分布转子振动的矩形截面柔性长梁振动控制抑制模块（RVM）最近在[132]中进行了研究，其中两个转子模块沿梁分布，其设计经过了优化，以最大限度地提高纵向垂直面上产生的推力，扭转扭矩最小。此外，通过最大化可控性Gramian解决了最优布局问题，并通过实验证明了振动抑制（见图4）。

图5. 互连驱动多体设计示例（从上到左）：1. HYDRUS [105. ；2. 飞爪[146. ；3. DFA [147. ；4. 龙[148]；5） 飞行拉斯德拉[149]；6）LASDRA行动[109]。

V. Interconnected Actuated Multibody Designs 本

节介绍了最近出现的一类空中机器人平台由多个铰接连杆或机构组成，通过被动或驱动关节相互机械连接，并通过分布在其上的倾斜或倾斜转子飞行。这种平台可以在改变形状的同时飞行，因此可以实现如下新颖场景：

1) 通过直接使用物体的身体进行空中抓取；
2) 通过蛇形运动在杂乱环境中进行空中作业；
3) 超大型机器人，可以进行空中操纵，无需操作时间短、有效载荷低、控制和传感困难等经典问题；
4) 游乐园中的铰接飞行角色。

Anzai等人[104]、Park等人[149]和Shi等人[150]介绍了具有二维多链路（HYDRUS）平台的水平可变形空中机器人（带二维多链路的可变换多转子）。每个连杆模块由一个带封闭笼的转子和一个伺服电机组成，其旋转轴与转子的旋转轴平行。因此，机器人可以在水平面上改变形状，同时保持典型多旋翼的悬停效率。该平台还演示了考虑摩擦锥约束以及转子和伺服电机驱动限制的整体空中抓取和运输箱形物体（见图5）。该HYDRUS平台在[152]中也用于运输多个

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objects at the same time by hanging them via cables. For this problem, the platform configuration, namelly the shape in the horizontal plane, is optimized to minimize the required thrust of each rotor while balancing the loading among the rotors. This HYDRUS was further extended in [104], where the horizontal plane transformable aerial robot with closed-loop multilinks structure (HALO) platform was presented. HALO is based on HYDRUS, yet, making a closed-loop link to increase the platform rigidity while also using 20°-tilted rotors to improve the horizontal motion performance. HALO was used to transport a planar payload attached parallel to the platform through short cables to mitigate uncontrollable payload oscillations [9]. Again the platform configuration is optimized to minimize the mass-center offset between the platform and the payload reducing steady-state hovering torque. An evolution of such a vehicle that is fully-actuated has been presented in [117].

Similar to HYDRUS and HALO platforms, one can find the flying gripper system proposed in [146]. It is designed as a modular closed-chain system, each module consisting of an off-the-shelf Crazyflie 2.0 quadrotor with a carbon fiber cuboid cage around it. An axially magnetized cylindrical Neodymium Iron Boron magnet was attached on the vertical hinge of each cuboid to allow them to rotate about the thrust direction of the quadrotors. A four-cuboid flying gripper system was then constructed and experimented to grasp a paper cup by squeezing the aperture angle of the four-bar linkage closed-chain among the four cuboids (see Fig. 5). Related to the previous platforms there is also the distributed flight array (DFA) of [147] (see Fig. 5). It is also constructed as a modular system, each module consisting of a rotor and driving wheels, so that, only when they form an array (using the wheels), they can fly together. However, in this case, the array structure is fixed and not actuated.

On the other hand, Oung *et al.* [147] proposed the dual-rotor embedded multilink robot with the ability of multi-DoFs aerial transformation (DRAGON) platform, consisting of multiple carbon fiber pipe modules, on each of which two parallel rotors were attached via a two-DoFs thrust vectoring mechanism (i.e., dual-rotor gimbal module). The pipe module itself was then connected with other modules via a two-DoFs orthogonal-axes joint with a pulley transmission with high reduction ratio. This reduces the back-drivability of the joint, thereby, mitigating possible vibration propagation through these joints. In contrast to the HYDRUS and HALO platforms, the DRAGON platform is fully-actuated, capable of assuming any pose and shape in SE(3) (up to the joint and rotor limits). Flying with fixed and changing shapes was experimentally demonstrated in [148] (see Fig. 5), also performing PP operations [106].

Another research along the same line is based on the large-size aerial skeleton with distributed rotor actuation (LASDRA) platform [109], [149]. Each link is based on the ODAR robot [81] and connected via string to maximize the dexterity of the motion. The LASDRA system aims at overcoming the well-known challenges in aerial manipulation (e.g., limited battery and payload, difficulty of on-board sensing and control, etc.) by making the robot large enough so that it can perform aerial manipulation tasks while tethered to the ground (or other vehicles). The "base" could provide abundant power and, consequently, the possibility of using powerful rotors. The mechanical structure of the LASDRA platform also provides the inherent stabilizing

TABLE IV
TELEOPERATION FEATURES FOR AERIAL PHYSICAL INTERACTION

Aerial platform		Reference	Human interface	Task	Level of maturity
Single	UDT	[154]	haptic	point contact and push	simulation
	MDT	[155]	haptic and 3D view	pick & place	experiment
Multiple	UDT	[142], [156]	haptic	manip.	simulation
	MDT	[101]	haptic	manip.	experiment

inertial/dissipative effects, while making the state estimation problem easier by enforcing the kinematic relations (measurable by, e.g., IMUs) from the (known) base to the end-effector.

Outdoor autonomous flights of a 3 m-long 3-link 15-DoFs untethered LASDRA system was demonstrated in [149], where the estimation accuracy was substantially improved (i.e., inter-link position RMSE less than 5 cm) by fusing the kinematic constraints and the distributed IMU and GNSS sensors in the form of semidistributed extended Kalman filtering. The method provides stable autonomous flight while avoiding excessive internal forces within the system (see Fig. 5). Various manipulation tasks with a 3m-long 2-link 6-DoFs operational LASDRA system were also demonstrated in [109], where compliant turning of an industrial valve was achieved based on the back-drivability of the BLDC rotors (see Fig. 5). This LASDRA system is scalable, i.e., with each link addressing its own weight, arbitrary number of links can be added indefinitely. To support this scalability, a distributed impedance control law was designed and applied to each individual link of the LASDRA systems [109], [149].

VI. Teleoperation

Because of the increasing number and complexity of applications in which aerial robots could be applied, methods that allow human intervention and supervision are required. It is indeed of fundamental importance, for safety and regulatory reasons, to let a human operator remain in the loop while the robotic system acts on the environment in an autonomous or semiautonomous way [28]. The majority of the presented works on aerial teleoperation at date focused on the contact-free motion control of the vehicles (see, e.g., [126], [153] and references therein). Bilateral (e.g., with haptic feedback) teleoperation methods have been presented to help humans controlling single [153] and multiple aerial vehicles navigating in cluttered environments. In the following, we present the most important recent works on the teleoperation of aerial systems with particular regard to aerial physical interaction and manipulation. Table IV gathers the main features of the state of the art on teleoperation for aerial physical interaction.

Considering *uni-directional thrust platforms*, teleoperation solutions focused on the case in which the platform is equipped with a simple rigid tool. In [154], a bilateral haptic feedback method has been proposed to address tasks like point contact, and pull/push. To increase the payload and the manipulation capabilities, a similar solution for a multirobot scenario is proposed in [142] and [156]. In these works, the fleet of robots is employed as a flying hand to remotely manipulate objects. However, likely

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同时通过电缆悬挂物品。针对这个问题，对平台配置（即水平面形状）进行了优化，以最小化每个转子所需的推力，同时平衡转子之间的负载。该HYDRUS在[104]中进一步扩展，其中介绍了具有闭环多链路结构（HALO）平台的水平面可变换空中机器人。HALO是基于HYDRUS的，但是，它制作了一个闭环连杆来增加平台的刚度，同时还使用了20°倾斜的转子来改善水平运动性能。HALO用于通过短电缆传输平行于平台的平面有效载荷，以减轻不可控的有效载荷振荡[9]。再次优化平台配置，以最小化平台和有效载荷之间的质心偏移，从而降低稳态悬停扭矩。[117]中介绍了这种完全驱动车辆的演变。

与HYDRUS和HALO平台类似，我们可以发现[146]中提出的飞爪系统。它被设计成一个模块化的封闭链系统，每个模块由一个现成的Crazyflie 2.0四转子组成，周围有一个碳纤维长方体笼。在每个长方体的垂直铰链上安装了一个轴向磁化的圆柱形钕铁硼磁铁，使其能够绕四个转子的推力方向旋转。然后构建了一个四长方体飞行夹持器系统，并通过挤压四个长方体之间的四连杆闭链的开口角来抓取纸杯（见图5）。与之前的平台相关的还有[147]的分布式飞行阵列（DFA）（见图5）。它还被构造成一个模块化系统，每个模块由一个转子和驱动轮组成，因此，只有当它们形成阵列（使用轮子）时，它们才能一起飞行。然而，在这种情况下，阵列结构是固定的，不会启动。

另一方面，翁等人[147]提出了双转子具有多自由度空中转换能力的嵌入式多链路机器人（DRAGON）平台，由多个碳纤维管模块组成，每个模块上通过一个双自由度推力矢量机构（即双转子框架模块）连接两个平行转子。然后，管道模块本身通过两个自由度正交轴接头与其他模块连接，该接头带有高减速比的皮带轮传动。这会降低接头的后部可驱动性，从而减轻可能通过这些接头传播的振动。与HYDRUS和HALO平台相比，DRAGON平台是完全驱动的，能够在se（3）中呈现任何姿势和形状（直到关节和转子极限）。[148]中对固定和改变形状的飞行进行了实验演示（见图5），也进行了PP操作[106]。

同一路线上的另一项研究是基于具有分布式转子驱动的大型空中骨架（LASDRA）平台[109], [149]。每个连杆都基于ODAR机器人[81]，并通过绳子连接，以最大限度地提高运动的灵活性。LASDRA系统旨在克服众所周知的空中操纵挑战（例如，电池和有效载荷有限，车载传感和控制困难等），使机器人足够大，以便在拴在地面（或其他车辆）上时执行空中操纵任务。"基地"可以提供充足的动力，因此，可以使用强大的转子。LASDRA平台的机械结构也提供了固有的稳定性

表IV
空中物理交互的遥操作特性

Aerial platform		Reference	Human interface	Task	Level of maturity
Single	UDT	[154]	haptic	point contact and push	simulation
	MDT	[155]	haptic and 3D view	pick & place	experiment
Multiple	UDT	[142], [156]	haptic	manip.	simulation
	MDT	[101]	haptic	manip.	experiment

惯性/耗散效应，同时通过加强从（已知）基座到末端效应器的运动学关系（如IMU可测量），使状态估计问题变得更容易。

[149]中展示了一个3米长的3-link 15自由度无约束LASDRA系统的户外自主飞行，通过以半分布式扩展卡尔曼滤波的形式融合运动学约束和分布式IMU和GNSS传感器，大大提高了估计精度（即，互连位置RMSE小于5厘米）。该方法提供了稳定的自主飞行，同时避免了系统内部的过度内力（见图5）。[109]中还演示了3米长的2连杆6自由度操作LASDRA系统的各种操作任务，其中基于BLDC转子的后驱动能力实现了工业阀门的合规转动（见图5）。LASDRA系统是可伸缩的，即每个链接都有自己的权重，可以无限期地添加任意数量的链接。为了支持这种可扩展性，设计了分布式阻抗控制律，并将其应用于LASDRA系统的每个单独链路[109], [149]。

VI. Teleoperation

由于航空机器人应用的数量和复杂性不断增加，因此需要允许人工干预和监督的方法。出于安全和监管原因，当机器人系统以自主或半自主方式作用于环境时，让人类操作员留在回路中确实非常重要[28]。目前，大多数关于空中遥控的工作都集中在飞行器的无接触运动控制上（例如，参见[126]、[153]和其中的参考文献）。双边（例如，通过触觉反馈）遥操作方法已被提出，以帮助人类控制单个[153]和多个飞行器在杂乱的环境中导航。在下文中，我们将介绍有关空中系统遥操作的最重要的最新工作，特别是有关空中物理交互和操纵的工作。表四汇总了空中物理交互遥操作技术的主要特点。

考虑到单向推力平台，远程操作解决方案侧重于平台配备简单刚性工具的情况。在[154]中，提出了一种双边触觉反馈方法来解决点接触和拉/推等任务。为了增加有效载荷和操纵能力，在[142]和[156]中提出了多机器人场景的类似解决方案。在这些工作中，机器人舰队被用作远程操纵物体的飞行手。然而，很可能

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due to its complexity, such solution has been validated only in simulation.

To develop hardware-in-the-loop simulators for physical interaction tasks, De Stefano *et al.* [157] used an industrial arm equipped with an additional smaller manipulator to simulate an aerial manipulator interacting with the environment. The problem of rendering the robot dynamics and the interaction forces is addressed. The latter can be then used in a haptic-feedback scenario to test specific teleoperation methods.

Considering *multidirectional thrust and fully-actuated platforms*, the literature focused on designing teleoperation solutions for P&P tasks. The teleoperation of the cable-suspended aerial manipulator *SAM* equipped with an articulated arm is shown in [155]. The authors proposed the use of a 3-D visual plus haptic feedback helping the user to drive the end-effector toward the grasp of a object. Staub *et al.* [101] addressed the teleoperation problem of a heterogeneous multirobot system composed of aerial and ground manipulators that cooperatively manipulate long objects.

From the human point of view, the common feedback used to help the telemanipulation are as follows.

1) *Visual:* from robot to human, cameras mounted on the aerial platform or on the end-effector are employed to provide 2-D or even 3-D images [155] to the operator. These information can also be integrated with head mounted displays in a virtual reality framework [158], [159] helping the operator performing the task. On the other hand, in [156], a red-green-blue-depth (RGBD) camera is used to extract human commands from the motion of his/her hand, which are then translated into robotic actions.
2) *Haptic:* haptic devices provide a sense of touch to the human. Using delta type haptic devices, one can apply 3-D forces to the human to augment his/her situational awareness. In [101], the haptic device is used to send the desired pose of the manipulated object from the human to the robotic system. In the other sense, it is used to apply on the human hand forces that are related to the inertia of the system and the presence of obstacles. In [154], the delta device is used to control the interaction forces of a quadrotor platform equipped with a rigid tool. The operator, moving the end-effector of the device, sends desired forces at the end-effector of the robot. On the other hand, the haptic device is used to apply to the user forces that give the perception of the contact force applied by the robot to the environment. These forces are also used to give the feeling of the distance from zero-commanded force.

VII. Perception and Planning

A. Motivation and Requirements

Three phases can be distinguished in aerial manipulation operations as follows:

1) navigation from the take-off position to the proximity of the workspace ensuring collision avoidance and reactivity in case of unexpected obstacles;
2) approaching to the desired operation position with higher accuracy;

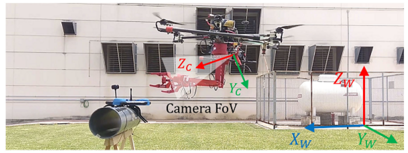

Fig. 6. Aerial manipulator grasping a crawler.

3) manipulation with accurate position and interaction control.

Phases 1) and 2) should consider perception to avoid collisions of a load being transported, also involving perception-based localization and accurate SLAM in GNSS denied environments. Object detection, tracking and localization are required for grasping and manipulation in phase 3), being distinctive of aerial manipulators when compared to other aerial robots. Motion planning also requires particular care in aerial manipulation. The dynamic coupling between the manipulator and the aerial platform should be considered at the motion planning level to prevent undesired position deviations that may result in collisions with the environment. Therefore, the planner should consider the full body dynamics and compute an optimal trajectory for every DoF.

B. Perception

Perception functionalities are needed for localization and mapping as well as for object detection and manipulation.

1) Localization and Mapping: UAV navigation is usually based on GNSS. The position provided by GNSS is used to close position control loops and to track desired trajectories. However, in many cases, the relative low frequency and the accuracy degradation due to the satellite visibility and communication problems, precludes its fully autonomous application. There are also many AEROM's applications in GNSS denied environments that require alternative approaches based on environment perception. In the following, we review localization methods and technologies for contact-free and manipulation operations, e.g., while transporting a load with the arms, or while performing contact-based inspection.

Odometry based on the combination of IMU and vision, with no absolute localization [160], is a well-known approach that has been applied in aerial manipulation. In [39], visual-inertial fusion with event cameras is presented. The use of event cameras offers significant advantages over standard cameras providing a very high dynamic range, very small latency, and no motion blur, which are relevant characteristics for AEROMs in noncontrolled outdoor environments.

Visual localization and SLAM methods were also applied. Absolute 3-D localization in the world frame $\mathcal{W}$ (see Fig. 6) and mapping can be performed from measurements obtained by multimodal sensorial approaches using 3-D LIDAR, stereo cameras, and radio range measurements w.r.t. beacons (see [43, Chapter IV.2]). Ultra wide band time-of-flight sensors are applied to compute the position of a receiver on-board the aerial robot, by means of triangulation and range only estimation, based on

这篇文章已被接受收录在本刊未来的一期中。除分页外，内容均为最终内容。

由于其复杂性，此类解决方案仅在仿真中得到验证。

为了开发用于物理交互任务的硬件在环仿真器，De Stefano等人[157]使用了一个配备了另一个较小机械手的工业机械臂来模拟与环境交互的空中机械手。解决了绘制机器人动力学和交互力的问题。后者可用于触觉反馈场景，以测试特定的遥操作方法。

考虑到多向推力和全驱动平台，文献侧重于为P&P任务设计远程操作解决方案。[155]中显示了配备铰接臂的悬索式空中机械手SAM的远程操作。作者建议使用三维视觉加触觉反馈，帮助用户驱动末端效应器抓住物体。Staub等人[101]研究了由空中和地面机械手组成的异构多机器人系统的遥操作问题，这些机械手可以协同操作长物体。

从人类的角度来看，用于帮助远程操作的常见反馈如下。

1) 视觉：从机器人到人类，安装在空中平台或末端执行器上的摄像头用于向操作员提供二维甚至三维图像[155]。这些信息还可以与虚拟现实框架中的头戴式显示器集成[158], [159]，帮助操作员执行任务。另一方面，在[156]中，红-绿-蓝深度（RGBD）摄像头用于从他/她的手的运动中提取人类命令，然后将其转换为机器人动作。
2) 触觉：触觉设备为人类提供触觉。使用delta型触觉设备，人们可以向人类施加三维力，以增强其情境意识。在[101]中，触觉设备用于将操纵对象的期望姿势从人类发送到机器人系统。从另一个意义上讲，它是用来施加在人手上的力，这些力与系统的惯性和障碍物的存在有关。在[154]中，delta装置用于控制配备刚性工具的四转子平台的相互作用力。操作员移动设备的末端执行器，向机器人的末端执行器发送所需的力。另一方面，触觉设备用于应用于用户力，从而感知机器人对环境施加的接触力。这些力也被用来给人一种距离零指令力的感觉。

七、感知和规划

A. 动机和要求

空中操纵操作可分为以下三个阶段:

1) 从起飞位置到工作区附近的导航，确保在遇到意外障碍物时避免碰撞和反应；
2) 以更高的精度接近所需的操作位置；

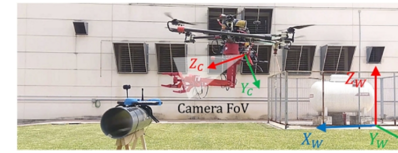

图6. 抓取爬虫的空中机械手。

3) 操作准确的位置和互动控制。

第1）和第2）阶段应考虑感知，以避免运输的负载发生碰撞，还包括基于感知的定位和在GNSS拒绝的环境中的精确SLAM。目标检测、跟踪和定位是第3阶段抓取和操作所必需的，与其他航空机器人相比，这是航空机器人的独特之处。在空中操作中，运动规划也需要特别小心。应在运动规划级别考虑机械手和空中平台之间的动态耦合，以防止可能导致与环境碰撞的意外位置偏差。因此，规划人员应考虑全身动力学，并为每个自由度计算最佳轨迹。

B. 感知

定位和映射以及目标检测和操纵都需要感知功能。

*1) 定位和测绘：*无人机导航通常基于GNSS。GNSS提供的位置用于关闭位置控制回路和跟踪所需的轨迹。然而，在许多情况下，由于卫星的能见度和通信问题，其相对低频率和精度降低，妨碍了其完全自主应用。还有许多AEROM在GNSS拒绝环境中的应用，需要基于环境感知的替代方法。在下文中，我们将回顾无接触和操纵操作的定位方法和技术，例如，在用手臂运输负载时，或在执行基于接触的检查时。

基于IMU和视觉组合的里程计，没有绝对定位[160],是一种已应用于空中操纵的众所周知的方法。在[39]中，介绍了带有事件摄像机的视觉惯性聚变。与标准摄像机相比，事件摄像机的使用具有显著的优势，可以提供非常高的动态范围、非常小的延迟和无运动模糊，这是AEROMs在非受控室外环境中的相关特征。

视觉定位和SLAM方法也被应用。利用三维激光雷达、立体相机和无线电距离测量（见[43,第IV.2章]）信标，通过多模态传感方法获得的测量值，可以在世界范围内进行绝对三维定位（见图6）和映射。超宽带飞行时间传感器用于计算空中机器人上接收器的位置，方法是基于

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a decentralized Extended Information filter combined with a particle filter for initialization. This can be applied at relatively long distances but the emitters should be well distributed; the method is affected by reflections, and the orientation cannot be obtained. Moreover, they provide position estimation with only about 0.5 m accuracy. When the robot is tens of meters from objects, a 3-D LIDAR provides a better accuracy and reliability. Finally, at small distances, stereo cameras can be applied and fuse the point clouds resulting from the camera with those provided by the 3-D LIDAR. In [38], a multisensor six-DoFs localization method is applied. An iterative closest point (ICP) algorithm extended to consider 3-D–3-D matchings between LIDAR (3-D distances) or cameras (distances in the SURF space) is used in the prediction stage. Also, the ICP can be easily combined with the IMU, optimizing the joint (laser and camera) error. The method can be implemented in real time with moderate computational cost on-board the robot. These methods have been implemented without any marker and by using measurements obtained at tens of meters with rms errors between 0.11 and $0.21\,\mathrm{m}$. Greater accuracy in relative localization can be obtained by means of markers. In particular, with visual markers it is possible to obtain the position with an accuracy better than 5 mm at a distance of 0.7 m by means of image processing. The method, presented in [43, Chapter IV.4], is based on optimizing the alignment of deformable contours from textureless images.

2) Object Detection: Object detection is strongly dependent on the used sensors. The payload of the aerial robot is a very important constraint. Then, visual cameras with light optics are the most used sensors. In aerial manipulation two different problems exist: the detection of objects to be manipulated at a certain distance (usually meters) in order to perform the approach, and the detection for grasping and manipulation. The first is a rough detection based on the following:

1) features, related for example to shape and color;
2) templates of the target object, which could be fixed or deformable to adapt to changes of the viewing angle due to the motion of the aerial robot;
3) classifiers, which could be also based on particular features.

Moreover, there are methods based on motion analysis that also use features or templates. The deep learning classifiers extracting image features are being applied more and more.

On the other hand, the detectors for grasping and manipulation should provide high accuracy. Methods based on markers, i.e., fiducial markers, have been proposed. In [43, Chapter IV.6] markers detection libraries and deep learning are applied. It is also possible to avoid the use of markers and apply modeling techniques of the objects to be manipulated. Particularly, Gaussian process implicit surfaces (GPIS) [161] takes into account the environment uncertainties involved in computer vision. This probabilistic information has been used in the H2020 AEROARMS project to generate grasp configurations. Moreover, the model is used to compute the relative 3-D pose. Fig. 6 shows an outdoor crawler detection and grasping with a dual arm. The GPIS models the crawler surface computing a covariance term for each point of the approximated surface. Alternatively, RGB-D cameras and convolutional neural networks can be used to obtain in real-time a suitable model for

Fig. 7. Two aerial manipulators assembling a structure (left). Long reach aerial manipulator with dual arm transporting a bar (right).

grasping. The state variables in the estimation of points of the object in the camera reference frame of Fig. 6 is given by $[{}^C\boldsymbol{p}_{[t]}, {}^C\boldsymbol{\eta}_{[t]}, {}^C\dot{\boldsymbol{p}}_{[t]}, {}^C\boldsymbol{\omega}_{[t]}]^\top$, where ${}^C\boldsymbol{p}_{[t]}$, ${}^C\boldsymbol{\eta}_{[t]}$, ${}^C\dot{\boldsymbol{p}}_{[t]}$, and ${}^C\boldsymbol{\omega}_{[t]}$ are, respectively, the position, orientation, linear velocity, and angular velocity in the camera frame $\mathcal{C}$ shown in Fig. 6 at the time instant t. These variables can be estimated by means of an extended Kalman filter. The resulting estimations of the centroid of the object to be grasped ${}^C\boldsymbol{p}$, ${}^C\boldsymbol{\eta}$ are used to compute the grasping points of the bar handle by means of the model of the object. Then, the references for the grasping point of each arm can be obtained as $[{}^E\boldsymbol{p}^i, {}^E\boldsymbol{\eta}^i]^\top = {}^E\boldsymbol{T}^i_C[{}^C\boldsymbol{p}_{[t]}, {}^C\boldsymbol{\eta}_{[t]}]^\top$, where ${}^E\boldsymbol{p}^i$ and ${}^E\boldsymbol{\eta}^i$ for $i = 1, 2$ are the position and orientation of the grasping points for the arms in the end-effector frame, $\mathcal{E}$, and ${}^E\boldsymbol{T}^i_C$ is the transformation from $\mathcal{C}$ to $\mathcal{E}$ for the arm i. These references can be passed to control methods described in Section III. Position based [27], [162] or image-based visual servoing [40], [163] can be used, expressing the error and control inputs directly in the image space, minimizing the error w.r.t. desired image feature coordinates.

C. Planning

1) Planning Levels: The higher level in planning of aerial manipulators is mission planning, e.g., the plan to assemble a structure from separate parts by taking into account the constraints related to the final desired state, the location of the parts, the connectors and the tools (see Fig. 7 left). The second level is the planning of the individual tasks to achieve the previously obtained assembly plan. In case there are several aerial robots, the task planner should allocate tasks to the different robots. The lower level is the motion planner, which is in charge of computing the trajectories of the robots, in such a way that the end-effectors of the aerial manipulators perform the previously specified tasks.

The abovementioned decomposition simplifies the inherent complexity of the aerial manipulation planning. Assembly and task planning are symbolic and consist of sequences of actions. These actions involve the motion of the aerial robots whose feasibility should be checked taking into account constraints, including the geometric ones. In [164], task and motion planning are interleaved in such a way that geometric constraints involved in the symbolic actions are checked and the plans are modified until the geometric constraints are satisfied. This requires to build and maintain a geometric counterpart of the symbolic plan to ensure that the current geometric state matches the current symbolic state.

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一种分散的扩展信息滤波器，结合粒子滤波器进行初始化。这可以应用在相对较长的距离，但发射器应分布均匀；该方法受反射影响，无法获得方向。此外，它们提供的位置估计精度仅为0.5 m左右。当机器人距离物体数十米时，三维激光雷达提供了更好的精度和可靠性。最后，在小距离处，可以应用立体相机，并将相机产生的点云与三维激光雷达提供的点云进行融合。在[38]中，采用了多传感器六自由度定位方法。在预测阶段，使用了一种迭代最近点（ICP）算法，该算法扩展到考虑激光雷达（三维距离）或相机（海浪空间中的距离）之间的三维-三维匹配。此外，国际比较项目

可轻松与IMU组合，优化接头（激光和相机）错误。该方法可以在计算机上实现

在机器人上实时且计算量适中。这些方法在没有任何标记的情况下实施，并使用在数十米处获得的测量，均方根误差在0.11到0.21米之间。通过标记可以获得更高的相对定位精度。特别是，使用视觉标记，可以通过图像处理在0.7 m的距离处获得精度优于5 mm的位置。[43,第四章4]中介绍的方法基于优化无纹理图像中可变形轮廓的对齐。

2）目标检测：目标检测强烈依赖于使用的传感器。空中机器人的有效载荷是一个非常重要的约束条件。然后，带有光学元件的视觉摄像机是最常用的传感器。在空中操纵中，存在两个不同的问题：探测在一定距离（通常为米）处操纵的物体，以执行接近，以及探测抓取和操纵。第一种是基于以下内容的粗略检测：

1) 与形状和颜色相关的特征；
2) 目标物体的模板，可以固定或变形，以适应由于空中机器人的运动而引起的视角变化；
3) 分类器，也可以基于特定的特征。

此外，还有一些基于运动分析的方法也使用特征或模板。提取图像特征的深度学习分类器得到了越来越多的应用。

手部探测器应提供高精度的抓取和其他操作。已经提出了基于标记的方法，即基准标记。在[43,第四章6]中，标记检测库和深度学习被应用。还可以避免使用标记，并对要操纵的对象应用建模技术。特别是，高斯过程隐式曲面[161]考虑了计算机视觉中涉及的环境不确定性。该概率信息已在H2020航空武器项目中用于生成抓取配置。此外，该模型还用于计算相对三维姿态。图6显示了一种带有双臂的户外爬虫检测和抓取。GPIS为爬虫曲面建模，计算近似曲面的每个点的协方差项。或者，RGB-D摄像机和卷积神经网络可用于实时获得合适的模型

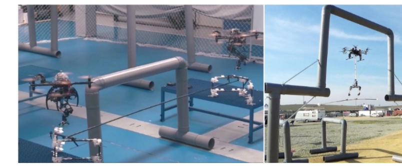

图7. 两个空中操纵器组装一个结构（左）。长距离空中机械手，双臂运输杆（右）。

抓给出了图6的相机参考帧中的对象点的估计中的状态变量通过 $_{[t]}$, ${}^C\boldsymbol{\eta}_{[t]}$, ${}^C\dot{\boldsymbol{p}}_{[t]}$, ${}^C\boldsymbol{\omega}_{[t]}$],其中^{C}p $_{[t]}$, ${}^C\boldsymbol{\eta}_{[t]}$, ${}^C\dot{\boldsymbol{p}}_{[t]}$,以及
[^{C}p
${}^C\omega_{[t]}$分别是图6所示的相机帧中的位置、方向、线速度和角速度 C
这些变量可以用卡尔曼滤波器的瞬时时间来估计。所得到的被抓取物体的质心估计^{C}p, ${}^C\eta$用于通过物体模型计算杆柄的抓取点。然后,每个手臂抓取点的参考值可以得到为
[${}^E p^i$,${}^E\eta^i$=${}^E T^i$[${}^C p_{[t]}$,${}^C\eta_{[t]}$],其中
${}^E p^i$和${}^E\eta^i$对于i = 1, 2是
末端效应器框架中手臂的抓取点,${}^E T^i$是手臂i从到的变换。E
这些参考可以传递给第三节中描述的控制方法。可以使用基于位置的[27]、[162]或基于图像的视觉伺服[40]、[163]，直接在图像空间中表达误差和控制输入，将误差w.r.t.所需图像特征坐标降到最低。

C.规划

1）规划级别：空中操纵器规划的更高级别是任务规划，例如，通过考虑与最终所需状态、零件位置、连接器和工具相关的约束，从单独的零件组装结构的计划（见图7）。第二个层次是对单个任务的规划，以实现之前获得的装配计划。如果有多个空中机器人，任务规划人员应将任务分配给不同的机器人。下一级是运动规划器，负责计算机器人的轨迹，从而使空中操纵器的末端执行器执行之前指定的任务。

上述分解简化了空中操纵规划的固有复杂性。装配和任务规划是象征性的，由一系列动作组成。这些动作涉及空中机器人的运动，其可行性应在考虑约束条件（包括几何约束）的情况下进行检查。在[164]中，任务和运动规划以这样一种方式交错，即检查符号动作中涉及的几何约束，并修改计划，直到几何约束得到满足。这需要构建和维护符号平面的几何对应物，以确保当前几何状态与当前符号状态匹配。

2) Assembly and Task Planning Levels: The assembly planning (AP) uses a 3-D CAD model of the structure and generates the tuple $PR = \langle S, D \rangle$, where $S = \{s_1, \ldots, s_n\}$ is the ordered sequence of operations to assemble the structure and $D = \{d_1, \ldots, d_m\}$ is a set of dependencies between assembly operations. The dependency d_j is a tuple made of the target operation and the set of all other operations that should necessarily be performed before that one, with $d_j = \langle t_l, p_k \rangle$ which is the set of operations p_k that should be achieved before the operation t_l, where t_l is just the identifier of an operation s_l. The set p_k contains the list of identifiers for operations from S. The AP should take into account the connections between parts and the involved forces. Considering truss structure built with connectors and links (see Fig. 7 on the left), interaction and gravity forces should be considered for their assembly. There are tools, such as the bullet physics library, that can be used to check if a subset of assembled parts is self-sustaining and can remain indefinitely to the given configuration without external support (statically stable).

AP is an NP-hard problem [165], which can be represented using directed graphs where each vertex and edge represents an assembly component and the corresponding relationship, respectively. Each candidate sequence can be evaluated by an objective cost function to be optimized or by a penalty value if the candidate sequence leads to an unstable configuration. In [165], a discrete particle swarm optimization algorithm is applied. In [166], reverse disassembly sequences are used to determine the assembly, providing faster eliminations thanks to the increased number of constraints at the beginning. The assembly plan can be implemented using several aerial robots. Thus, the planner tries to combine successive actions into parallel operations to be executed at the same time by separate robots. The work in [43, Chapter V.1] implements interleaved task and motion planning of aerial robots by means of a Geometric task planner to perform the assembly of a truss structure. It includes actions devoted to the monitoring of the assembly actions by means of visual tracking of the robots. The resulting symbolic task plan has associated motions that should be also planned as follows.

3) Motion Planning: Many practical approaches for motion planning of aerial manipulators decouples the problem of the planning of the aerial platform and the manipulator. First, the algorithm plans a trajectory of the center of gravity (CoG) of the aerial platform that ends in a suitable position for manipulation, then the algorithm plans the motion of the end-effector, assuming that the aerial platform maintains the same position and orientation during the manipulation. These approaches have the following drawbacks.

1) The geometric approach is not able to deal with the orientation, which plays an important role in aerial manipulation.
2) The decoupling between the aerial platform and the manipulator could be inefficient from the energy point of view and execution time.
3) The abovementioned decoupling could be unfeasible when the motion of the robotic manipulator is needed to avoid obstacles (see Fig. 7).
4) The decoupling is also unfeasible when the motion of the manipulator has significant impact on the motion of the platform.

Kinodynamic planning allows the consideration of the kinematic and dynamic constraints in the motion of the aerial manipulator. A simple decoupling approach consists of a first step of geometric planning for a sphere bounding the aerial platform, by using, for example, RRT to compute segments with zero velocity and acceleration at end-points. Then, the path is transformed in a trajectory satisfying the kinematic and dynamic constraints. Finally, velocity and accelerations are modified along the local paths without modifying its geometry and ensuring collision avoidance [167]. In [168], control aware planning is proposed to maintain contact with a surface. There are also methods that consider jointly motion planning and control to maintain this contact [94]. In the AEROARMS project an RRT* algorithm was used for planning the simultaneous motion of the aerial platform and the joints of the arms transporting a bar in an environment with high density of obstacles, as shown in Fig. 7. A planar model with eight configuration variables for the aerial manipulator was used. The motion of the arms of the long reach aerial manipulator in Fig. 7 right when holding the bar, modifies the position of the CoG of the aerial robot and then the motion of the aerial platform. If this coupling is not considered, collisions may occur. In order to avoid these collisions an RRT* with dynamic awareness has been developed and implemented [169].

4) Reactivity: Aerial robots are often subject to disturbances, including nonmodeled aerodynamic effects, positioning inaccuracy, and others. This is particularly true for small outdoor aerial robots where the wind plays a significant role. Moreover, it is also difficult to consider all the unexpected objects and forces that could be involved in aerial manipulation. Then, reactivity is needed to increase the safety of AEROMs. Autonomous reactivity should be based on the perception capabilities of the AEROM, by including mainly range sensors, computer vision, and force/torque sensors. The abovementioned perception, planning, and reactivity functionalities were integrated for real-time execution in the AEROARMS project [28]. The system was implemented with an on-board 3-D laser and a computer to perform mapping and motion planning in real time (see Fig. 7 right).

VIII. New Generation of AEROMs

A. Challenges

1) Time of Flight and Range: The current time of flight of most AEROMs are minutes or tens of minutes, which is too short for many practical applications. The increasing of the flight time involves new configurations of aerial platforms, new sources of energy and even new control and motion planning methods. Some applications also require increased range, involving flights beyond the visual line of sight, which also implies the respect of regulations and safety norms.

2) Safety in the Interactions With Persons and Objects: AEROMs are based on multirotors and HLs. The energy of the propellers is a threat for people and valuable objects close the aerial manipulator. This is particularly true for applications such as aerial coworkers for physical interactions (see Fig. 8). Thus, it is necessary to develop safer platforms and new technologies to enhance safety.

2) 装配和任务规划级别：装配规划（AP）使用结构的三维CAD模型,并生成元组PR = S, D ,其中S = s_1,.. ，s_n是组装结构的有序操作序列，D = d_1，.. ，d_m是程序集之间的一组依赖项
操作 依赖项d_j是由目标组成的元组
操作以及在该操作之前必须执行的所有其他操作的集合，其中d_j = t_l, p_k是在操作t_l之前应该实现的操作集合p_k，其中t_l只是操作s_l的标识符。集合p_k包含来自的操作的标识符列表
AP应考虑部件之间的连接和相关的力。考虑到用连接件和连杆建造的桁架结构（见左图7），组装时应考虑相互作用和重力。有一些工具，比如bullet physics library,可以用来检查组装零件的子集是否能够自我维持，并且可以在没有外部支持的情况下无限期地保持给定的配置（静态稳定）。

AP是一个NP难问题[165],可以使用有向图来表示，其中每个顶点和边分别表示一个装配组件和相应的关系。每个候选序列都可以通过待优化的目标成本函数进行评估，如果候选序列导致配置不稳定，则可以通过惩罚值进行评估。在[165]中，采用了离散粒子群优化算法。在[166]中，反向拆卸顺序用于确定装配，由于开始时约束的数量增加，可以更快地消除。装配计划可以使用多个空中机器人来实现。因此，计划者试图将连续的动作组合成并行操作，由不同的机器人同时执行。[43,第V.1章]中的工作通过几何任务规划器实现了航空机器人的交叉任务和运动规划，以完成桁架结构的组装。它包括通过视觉跟踪机器人来监控装配动作的动作。由此产生的符号任务计划具有相关的动作，这些动作也应按如下方式计划。

3) 运动规划：运动规划的许多实用方法
空中机械手的规划将空中平台和机械手的规划问题解耦。首先，该算法规划空中平台重心（CoG）的轨迹，该轨迹在合适的操纵位置结束，然后该算法规划末端执行器的运动，假设空中平台在操纵期间保持相同的位置和方向。这些方法有以下缺点。

1) 几何方法无法处理在空中操纵中起重要作用的方向。
2) 从能量和执行时间的角度来看，空中平台和机械手之间的解耦可能是低效的。
3) 当需要机械手的运动来避开障碍物时，上述解耦可能不可行（见图7）。
4) 当机械手的运动对平台的运动有重大影响时，解耦也是不可行的。

Kinodynamic规划允许考虑空中机械手运动中的运动学和动力学约束。一种简单的解耦方法包括对包围空中平台的球体进行几何规划的第一步，例如使用RRT计算端点处速度和加速度为零的线段。然后，将路径变换为满足运动学和动力学约束的轨迹。最后，沿局部路径修改速度和加速度，而不修改其几何结构并确保避免碰撞[167. 。在[168. 中，提出了控制感知规划，以保持与表面的接触。还有一些方法考虑联合运动规划和控制来保持这种联系[94. 。在AEROARMS项目中，RRT*算法用于规划空中平台的同时运动，以及在高密度障碍物环境中运输杆的手臂关节，如图7. 示。采用了八个构形变量的平面模型。图7. 长距离空中机械手的手臂在握住杆时的运动，会修改空中机器人的CoG位置，然后修改空中平台的运动。如果不考虑这种耦合，可能会发生碰撞。为了避免这些碰撞，开发并实施了具有动态感知的RRT*[169. 。

4）反应性：空中机器人经常受到干扰，
包括非模型空气动力学效应、定位不准确性等。对于小型户外空中机器人来说尤其如此，因为风在其中起着重要作用。此外，还很难考虑空中操纵可能涉及的所有意外物体和力。然后，需要反应性来提高AEROMs的安全性。自主反应性应基于AEROM的感知能力，主要包括距离传感器、计算机视觉和力/扭矩传感器。上述感知、规划和反应功能被集成在航空武器项目中实时执行[28]。该系统由车载3-D激光器和计算机实现，以实时执行映射和运动规划（见图7）。

八、新一代AEROMS

A.挑战

1) 飞行时间和航程：大多数飞机当前的飞行时间为分钟或几十分钟，这对于许多实际应用来说太短了。飞行时间的增加涉及新的空中平台配置、新的能源，甚至包括新的控制和运动规划方法。一些应用还要求增加航程，包括超出视觉视线的飞行，这也意味着遵守法规和安全规范。

2) 与人和物体互动的安全性：AEROMs基于多转子和HLs。螺旋桨的能量对空中操纵器附近的人员和贵重物品构成威胁。这对于空中同事等物理交互应用尤其如此（见图8）。因此，有必要开发更安全的平台和新技术来提高安全性。

Fig. 8. AEROM providing a tool (left) and guiding a human (right).

3) Accuracy: The accuracy of AEROMs depends on the accuracy of the positioning sensors, and is limited by unavoidable perturbations, such as wind gust and aerodynamic effects due to nearby surfaces. Some of these effects can be modeled and controlled, but others are difficult to manage, especially with the limited on-board capabilities of light AEROMs.

4) Reliable Decisional Autonomy: Current AEROMs usually require human supervision. The increasing of decisional autonomy should involve high reliability by considering all the sources of faults and contingency measures.

Crossed effects between challenges are also present, e.g., the increase of decisional autonomy requires high on-board computational capabilities that are constrained by the minimization of payload to increase flight time and range.

B. Approaches

1) Energy: There are different approaches to save energy and, thus, increase the time of flight or the range.

1) *Perching:* Most research works in aerial manipulation assume that the operation is carried out in flight. However, in some cases, the robot could perch on support structures like poles or cables to avoid the waste of energy and extend the operation time. Some mechanisms for quadrotor perching have been proposed, including bioinspired passive mechanisms [170], grippers [171], or vacuum cups [172].
2) *Hybrid aerial-ground platforms:* Aerial locomotion requires significantly more energy than ground locomotion. Vehicles with hybrid locomotion can fly to sites that cannot be accessed by ground, land, perform the final approach by means of ground locomotion, and finally perform the task from the ground or attached to a static surface. This saves energy and increases the operation time [173].
3) *Hybrid fixed/rotary-wing platforms:* This includes aerial platforms integrating the beneficial features of fixed-wing (long flight time and range) and rotary-wing (vertical take-off and landing and hovering). In [174], these platforms are categorized into two types: convertiplanes and tail sitters. The former maintains the airframe orientation and switch between flight modes. It includes the tilt-wing platform [175], where the wing is partially or totally tilted together with the rotors during the flight-mode transition, and also dual systems, which have two sets of propulsion units: upward and forward mounted rotors for vertical motion and cruise flight, respectively. On the other hand, the tail sitter performs take-off and landing vertically on its tail while the entire airframe tilts to achieve cruise flight [176]. None of these platforms have been used up to now for aerial manipulation.
4) *Morphing and bioinspired approaches:* These include configurations inspired by birds and insects. Particularly, morphing technologies can be applied to change between a low drag configuration, typical in fixed wings, and high lift configuration to avoid stall at low speeds or even to hover [177]. It has also been shown that flapping-wing flight, so abundant in nature, is more efficient than rotary-wing flight [178], [179]. It is well known that birds are able to fly long distances minimizing the energy consumption. Several flapping unmanned aerial vehicles, called ornithopters, have been designed. The key aspect to save energy is the optimal combination of gliding and flapping. It has been also shown that the drag of the flapping wing is greater than fixed wing. Thus, the flap-gliding flight yields a performance advantage when comparing with only flapping. Furthermore, the maximum range performance achievable with flap-gliding flight and the associated optimal travelling speed have been determined [180]. In order to perform the optimal switching between flapping and fixed wing phases, it is necessary to obtain the velocity and height from which to start descending at a very low angle, maximizing the lift to drag ratio. Also the transitions from gliding to flapping to increase altitude or to perform perching is very important. Suitable models and new control and planning methods should be obtained. However, up to now, flapping-wing platforms have not been used for aerial manipulation. The ERC Advanced Grant GRIFFIN proposes the development of new bioinspired aerial manipulation systems with the capability to glide, saving energy, flap the wings, perch, fold the wing and manipulate. Martín-Alćantara *et al.* [53] introduced the concept of winged aerial manipulation robot, combining the manipulation with gliding to reduce the total weight of the aerial robot.

2) Safety: It involves both information processing and physical interactions. The former is related to situational awareness including environment perception for collision detection and avoidance. The second is related to AEROMs physically interacting with humans [181] (see Fig. 8), e.g., to provide tools at height [34] or to help in manipulation tasks.

3) Accuracy: The modeling and control of the aerodynamic effects can be considered to increase the accuracy of aerial manipulators in free flight. The sensing of airflow [182], the increasing of the control frequency, and implementations with new light servomotors, can be also used to cancel perturbations and increase the accuracy. Since the cancellation of all perturbations is difficult, an alternative strategy consists in manipulating the environment while perching or holding a fixed support with another arm.

4) Decisional Autonomy and Reliability: The complexity of the implementation of autonomous functionalities is related to the conditioning of the environment. The use of markers facilitates autonomous perception, as mentioned in Section VII-B. However, the variability of lighting conditions, as it is usually the case outdoors, plays an important role. On the other hand, perturbations are unavoidable and the aerial manipulator will deviate from the planned trajectory due, e.g., to wind gusts or to

图8. AEROM提供工具（左）和引导人（右）。

3) 精度：AEROMs的精度取决于定位传感器的精度，并受到不可避免的扰动的限制，如阵风和附近表面产生的空气动力学效应。其中一些影响可以建模和控制，但其他影响很难管理，尤其是在轻型飞机机载能力有限的情况下。

4) 可靠的决策自主性：目前的AEROMs通常需要人工监督。通过考虑所有故障源和应急措施，提高决策自主性应涉及高可靠性。

挑战之间也存在交叉效应，例如，决策自主性的增加需要较高的机载计算能力，这些能力受到有效载荷最小化的限制，以增加飞行时间和距离。

B.方法

1） 能源：有不同的方法来节省能源，从而增加飞行时间或航程。

1) 栖息：大多数关于空中操纵的研究工作都假设操作是在飞行中进行的。然而，在某些情况下，机器人可以栖息在杆子或电缆等支撑结构上，以避免能源浪费并延长操作时间。已经提出了一些用于四角头栖息的机制，包括仿生被动机制[170]、夹持器[171]或真空杯[172]。
2) 混合式空中地面平台：空中运动比地面运动需要更多的能量。具有混合动力运动的车辆可以飞到地面、陆地无法进入的地点，通过地面运动执行最终进近，最后从地面或附着在静态表面上执行任务。这节省了能源并增加了操作时间[173]。
3) 固定翼/旋转翼混合平台：包括结合固定翼（长飞行时间和航程）和旋转翼（垂直起飞、着陆和悬停）有益功能的空中平台。在[174]中，这些平台分为两类：敞篷飞机和尾座式。前者保持机身方向，并在飞行模式之间切换。它包括倾斜翼平台[175],其中机翼在飞行模式转换期间与转子一起部分或完全倾斜，以及双系统，其具有两套推进装置：分别用于垂直运动和巡航飞行的向上和向前安装的转子。另一方面，机尾座通过机尾垂直起降，同时整个机身倾斜以实现巡航航班[176]。到目前为止，这些平台都没有用于空中操纵。
4) 变形和生物灵感的方法：这些包括鸟类和昆虫灵感的配置。特别是，变形技术可以应用于在低阻力配置（通常在固定机翼中）和高升力配置之间切换，以避免低速失速，甚至悬停[177]。研究还表明，自然界中如此丰富的扑翼飞行比旋转翼飞行效率更高[178], [179]。众所周知，鸟类能够长距离飞行，从而将能源消耗降至最低。一些被称为扑翼机的扑翼无人机已经被设计出来。节能的关键是滑翔和拍打的最佳组合。研究还表明，扑翼的阻力大于固定翼。因此，与仅拍打相比，襟翼滑行飞行具有性能优势。此外，还确定了襟翼滑翔飞行可达到的最大射程性能和相关的最佳旅行速度【180】。为了在扑翼和固定翼阶段之间进行最佳切换，需要获得速度和高度，从该高度开始以非常低的角度下降，从而最大化升阻比。此外，从滑翔到拍打以增加高度或执行栖息的过渡也非常重要。应获得合适的模型和新的控制和规划方法。然而，到目前为止，扑翼平台还没有被用于空中操纵。ERC高级格兰特·格里芬（Grant GRIFFIN）提议开发新的仿生空中操纵系统，该系统具有滑行、节能、拍打机翼、栖息、折叠机翼和操纵的能力。Martín-Alc′antara等人[53]引入了有翼空中操纵机器人的概念，将操纵与滑翔相结合，以减轻空中机器人的总重量。

2) 安全：它涉及信息处理和物理-互动。前者与态势感知有关，包括用于碰撞检测和避免的环境感知。第二个与AEROMs与人类的物理交互有关[181]（见图8），例如，在高空提供工具[34]或帮助操作任务。

3) 精度：可以考虑对气动效应进行建模和控制，以提高自由飞行中航空机械手的精度。气流传感[182],控制频率的增加，以及采用新的光伺服电机的实施，也可用于消除扰动并提高精度。由于很难消除所有扰动，另一种策略是在用另一只手臂固定或支撑固定支架的同时操纵环境。

4) 决策自主性和可靠性：自主功能实现的复杂性与环境条件有关。如第VII-B节所述，标记物的使用有助于自主感知。然而，照明条件的可变性（通常是室外情况）起着重要作用。另一方面，扰动是不可避免的，由于阵风或其他原因，空中操纵器将偏离计划轨迹

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uncontrolled aerodynamic effects. It is then necessary to apply methods from Section VII-C to provide reactivity based on the perception of the environment. It is quite possible that, during manipulation operation, external perturbations will generate collisions. The effect of these collisions can be greatly reduced by having compliance, as shown in Section III. However, compliance worsens the accuracy. Thus, adaptive compliance should be a characteristic of future aerial manipulators.

The decisional autonomy is related to the on-board sensing, actuation, and computational capabilities. However, the hardware to implement these capabilities is constrained by the weight and energy consumption. Future processors will favor the implementation.

IX. Conclusion

In this article, we revised aerial robotic manipulation. This is a constantly growing domain in which we analyzed every aspect characterizing autonomous robots, ranging from the design and control of aerial manipulators to the perception and motion planning problems for physical interaction tasks.

Our analysis evinces that the research on aerial manipulation already provided aerial robots with great physical interaction capabilities. However, most of the experimental works done so far were conducted in structured indoor environments. Nevertheless, with the aim of increasing the precision and robustness of aerial manipulators for their application in real environments, the number of outdoor experimental investigations is increasing. These studies address all the challenges related to disturbances and uncertainty in outdoor conditions (e.g., wind gust, illumination, etc.) that dramatically impact robot performance.

Still, the great potential impact of aerial manipulation already pushed its use for industrial applications. Contact-based inspection is one of the first applications addressed but others will follow in domains like construction and maintenance. The challenges for the future and new approaches are related to the energy, safety, accuracy, and reliable decisional autonomy.

References

[1] A. Albers, S. Trautmann, T. Howard, T. Anh Nguyen, M. Frietsch, and C. Sauter, "Semi-autonomous flying robot for physical interaction with environment," in *Proc. IEEE Conf. Robot., Automat. Mechatronics*, 2010, pp. 441–446.

[2] D. Mellinger, Q. Lindsey, M. Shomin, and V. Kumar, "Design, modeling, estimation and control for aerial grasping and manipulation," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, San Francisco, CA, USA, 2011, pp. 2668–2673.

[3] Q. Lindsey, D. Mellinger, and V. Kumar, "Construction with quadrotor teams," *Auton. Robots*, vol. 33, no. 3, pp. 323–336, 2012.

[4] L. Marconi, R. Naldi, and L. Gentili, "Modelling and control of a flying robot interacting with the environment," *Automatica*, vol. 47, no. 12, pp. 2571–2583, 2011.

[5] T. DankoC. Korpela and P. Oh, "MM-UAV: Mobile manipulating unmanned aerial vehicle," *J. Intell. Robotic Syst.*, vol. 65, no. 1–4, pp. 93–101, 2012.

[6] M. Fumagalli *et al.*, "Developing an aerial manipulator prototype: Physical interaction with the environment," *IEEE Robot. Automat. Mag.*, vol. 21, no. 3, pp. 41–50, Sep. 2014.

[7] N. Michael, J. Fink, and V. Kumar, "Cooperative manipulation and transportation with aerial robots," Auton. Robots, vol. 30, pp. 73–86, 2011.

[8] N. Michael, S. Kim, J. Fink, and V. Kumar, "Kinematics and statics of cooperative multi-robot aerial manipulation with cables," in *Proc. Int. Design Eng. Tech. Conf. Comput. Informat. Eng. Conf.*, vol. 49040, 2009, pp. 83–91.

[9] J. Fink, N. Michael, S. Kim, and V. Kumar, "Planning and control for cooperative manipulation and transportation with aerial robots," *Int. J. Robot. Res.*, vol. 30, no. 3, pp. 324–334, 2011.

[10] Q. Jiang and V. Kumar, "The inverse kinematics of cooperative transport with multiple aerial robots," *IEEE Trans. Robot.*, vol. 29, no. 1, pp. 136–145, Feb. 2013.

[11] P. E. I. Pounds, D. R. Bersak, and A. M. Dollar, "Stability of small-scale UAV helicopters and quadrotors with added payload mass under PID control," *Auton. Robots*, vol. 33, no. 1/2, pp. 129–142, 2012.

[12] M. Bernard, K. Kondak, and G. Hommel, "Load transportation system based on autonomous small size helicopters," *Aeronaut. J.*, vol. 114, no. 1153, pp. 191–198, 2010.

[13] M. Bernard, K. Kondak, I. Maza, and A. Ollero, "Autonomous transportation and deployment with aerial robots for search and rescue missions," *J. Field Robot.*, vol. 28, no. 6, pp. 914–931, 2011.

[14] P. E. Pounds and A. Dollar, "Hovering stability of helicopters with elastic constraints," in *Proc. Dyn. Syst. Control Conf.*, 2010, pp. 781–788.

[15] P. E. I. Pounds and A. M. Dollar, "Stability of helicopters in compliant contact under PD-PID control," *IEEE Trans. Robot.*, vol. 30, no. 6, pp. 1472–1486, Dec. 2014.

[16] P. Pounds, D. Bersak, and A. Dollar, "Grasping from the air: Hovering capture and load stability," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2011, pp. 2491–2498.

[17] P. E. Pounds and A. M Dollar, "Aerial grasping from a helicopter UAV platform," in *Experimental Robotics*. Berlin, Germany: Springer, 2014, pp. 269–283.

[18] K. Kondak *et al.*, "Aerial manipulation robot composed of an autonomous helicopter and a 7 degrees of freedom industrial manipulator," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2014, pp. 2107–2112.

[19] F. Huber *et al.*, "First analysis and experiments in aerial manipulation using fully actuated redundant robot arm," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2013, pp. 3452–3457.

[20] A. E. Jimenez-Cano, J. Martin, G. Heredia, A. Ollero, and R. Cano, "Control of an aerial robot with multi-link arm for assembly tasks," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2013, pp. 4916–4921.

[21] M. Kamel, K. Alexis, and R. Siegwart, "Design and modeling of dexterous aerial manipulator," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2016, pp. 4870–4876.

[22] T. W. Danko, K. P. Chaney, and P. Y. Oh, "A parallel manipulator for mobile manipulating UAVs," in *Proc. IEEE Int. Conf. Technol. Practical Robot Appl.*, 2015, pp. 1–6.

[23] T. W. Danko and P. Y. Oh, "A hyper-redundant manipulator for mobile manipulating unmanned aerial vehicles," in *Proc. Int. Conf. Unmanned Aircr. Syst.*, 2013, pp. 974–981.

[24] M. Kobilarov, "Nonlinear trajectory control of multi-body aerial manipulators," *J. Intell. Robot. Syst.*, vol. 73, no. 1, pp. 679–692, 2014.

[25] K. Morton and L. F. G. Toro, "Development of a robust framework for an outdoor mobile manipulation UAV," in *Proc. IEEE Aerosp. Conf.*, Mar. 2016, pp. 1–8.

[26] V. Lippiello *et al.*, "Hybrid visual servoing with hierarchical task composition for aerial manipulation," *IEEE Robot. Automat. Lett.*, vol. 1, no. 1, pp. 259–266, Jan. 2016.

[27] C. Kanellakis, M. Terreran, D. Kominiak, and G. Nikolakopoulos, "On vision enabled aerial manipulation for multirotors," in *Proc. 22nd IEEE Int. Conf. Emerg. Technol. Factory Automat.*, 2017, pp. 1–7.

[28] A. Ollero *et al.*, "The aeroarms project: Aerial robots with advanced manipulation capabilities for inspection and maintenance," *IEEE Robot. Automat. Mag.*, vol. 25, no. 4, pp. 12–23, Dec. 2018.

[29] D. Brescianini and R. D'Andrea, "Computationally efficient trajectory generation for fully actuated multirotor vehicles," *IEEE Trans. Robot.*, vol. 34, no. 3, pp. 555–571, Jun. 2018.

[30] M. Kamel *et al.*, "The voliro omniorientational hexacopter: An agile and maneuverable tiltable-rotor aerial vehicle," *IEEE Robot. Automat. Mag.*, vol. 25, no. 4, pp. 34–44, Dec. 2018.

[31] M. Tognon and A. Franchi, "Omnidirectional aerial vehicles with unidirectional thrusters: Theory, optimal design, and control," *IEEE Robot. Automat. Lett.*, vol. 3, no. 3, pp. 2277–2282, Jul. 2018.

[32] M. Ryll *et al.*, "6D interaction control with aerial robots: The flying end-effector paradigm," *Int. J. Robot. Res.*, vol. 38, no. 9, pp. 1045–1062, 2019.

[33] M. Orsag, C. Korpela, P. Oh, and S. Bogdan, *Aerial Manipulation*. Berlin, Germany: Springer, 2018.

[34] A. Suarez, F. Real, V. M. Vega, G. Heredia, A. Rodriguez-Castaño, and A. Ollero, "Compliant bimanual aerial manipulation: Standard and long reach configurations," *IEEE Access*, vol. 8, pp. 88844–88865, May 2020.

这篇文章已被接受收录在本刊未来的一期中。除分页外，内容均为最终内容。

不受控制的空气动力学效应。然后有必要应用第VII-C节中的方法，根据对环境的感知提供反应性。在操纵操作期间，外部扰动很可能会产生碰撞。如第三节所示，这些碰撞的影响可以通过柔顺性大大降低。然而，柔顺性会降低精度。因此，自适应柔顺性应该是未来航空机械手的一个特征。

决策自主性与车载感知、驱动和计算能力有关。然而，实现这些功能的硬件受到重量和能耗的限制。未来的处理器将支持这种实现。

IX. Conclusion

在这篇文章中，我们修改了空中机器人操作。这是一个不断发展的领域，我们分析了自治机器人的各个方面，从空中机械手的设计和控制到物理交互任务的感知和运动规划问题。

我们的分析表明，对空中操纵的研究已经为空中机器人提供了强大的物理交互能力。然而，迄今为止所做的大多数实验工作都是在结构化的室内环境中进行的。然而，为了提高航空机械手在实际环境中应用的精度和鲁棒性，户外实验研究的数量正在增加。这些研究解决了与室外条件（例如阵风、照明等）中的干扰和不确定性相关的所有挑战，这些干扰和不确定性会显著影响机器人的性能。

尽管如此，空中操纵的巨大潜在影响已经推动了它在工业应用中的应用。基于接触的检查是首批解决的应用之一，但其他应用将在建筑和维护等领域跟进。未来的挑战和新方法与能量、安全性、准确性和可靠的决策自主性有关。

参考文献

[1] A. Albers、S. Trautmann、T. Howard、T. Anh Nguyen、M. Frietsch和
C. Sauter, "与环境进行物理交互的半自主飞行机器人"，在Proc。IEEE形态机器人。，自动装置。机电一体化，2010年，第441–446页。

[2] D. Mellinger、Q. Lindsey、M. Shomin和V. Kumar, "空中抓取和操纵的设计、建模、估计和控制"，在Proc。IEEE/RSJ Int. Conf. Intell。机器人系统。，美国加利福尼亚州旧金山，2011年，第2668–2673页。

[3] Q. Lindsey, D. Mellinger和V. Kumar, "四旋翼团队施工"，Auton。机器人，第33卷，第3期，第323-3362012页。

[4] L. Marconi、R. Naldi和L. Gentili, "与环境交互的飞行机器人的建模和控制"，Automatica,第47卷，第12期，第2571-25832011页。

[5] T、 丹科克。Korpela和P. Oh, "MM-UAV：移动操纵无人机"，J. Intell。机器人系统。，2012年，第65卷，第1–4期，第93–101页。

[6] M. Fumagalli等人，"开发空中机械手原型：与环境的物理交互"，IEEE Robot。自动装置。杂志，第21卷，第3期，第41–50页，2014年9月。

[7] N. Michael、J. Fink和V. Kumar, "空中机器人的协同操作和运输"，Auton。机器人，第30卷，第73–86页，2011年。

[8] N. Michael、S. Kim、J. Fink和V. Kumar, "多机器人电缆协同空中操纵的运动学和静力学"，在Proc。内部设计工程技术配置计算机。告密者。《工程配置》，2009年第49040卷，第83–91页。

[9] J. Fink, N. Michael, S. Kim和V. Kumar, "空中机器人协同操作和运输的规划和控制"，Int. J. Robot。Res.,第30卷，第3期，第324–334页，2011年。

[10] Q. Jiang和V. Kumar, "多空中机器人协同运输的逆运动学"，IEEE Trans。机器人第29卷第1期，第136–145页，2013年2月。

[11] P. E. I. Pounds、D. R. Bersak和A. M. Dollar, "在PID控制下，具有额外有效载荷质量的小型无人机直升机和四旋翼的稳定性"，Auton。《机器人》，第33卷，第1/2期，第129–142页，2012年。

[12] M. Bernard、K. Kondak和G. Hommel, "基于自主小型直升机的装载运输系统"，Aeronaut。《华尔街日报》，第114卷，第1153号，第191–198页，2010年。

[13] M. Bernard、K. Kondak、I. Maza和A. Ollero, "用于搜索和救援任务的空中机器人自主运输和部署"，J. Field Robot。，2011年第28卷第6期第914–931页。

[14] P. E.英镑和A.美元，"弹性约束下直升机的悬停稳定性"，在Proc。戴恩。系统。《控制形态》，2010年，第781–788页。

[15] P. E. I.磅和A. M.美元，"PD-PID控制下符合要求的直升机接触稳定性"，IEEE Trans。机器人第30卷第6期，第1472–1486页，2014年12月。

[16] P. Pounds、D. Bersak和A. Dollar, "从空中抓取：悬停捕获和负载稳定性"，在Proc中。IEEE内部配置机器人。自动装置。，2011年，第2491–2498页。

[17] 实验机器人学中的P. E.英镑和A.M.美元，"直升机无人机平台的空中抓取"。德国柏林：斯普林格出版社，2014年，第269–283页。

[18] K. Kondak等人，"由一架自主直升机和一个7自由度工业机械手组成的空中操纵机器人"，在Proc。IEEE内部配置机器人。自动装置。，2014年，第2107–2112页。

[19] F. Huber等人，"使用全驱动冗余机械臂进行空中操纵的首次分析和实验"，摘自Proc。IEEE/RSJ Int. Conf. Intell。机器人系统。，2013年，第3452–3457页。

[20] A. E.希门内斯·卡诺、J.马丁、G.埃雷迪亚、A.奥利罗和R.卡诺，"装配任务用多连杆臂空中机器人的控制"，在Proc。IEEE内部配置机器人。自动装置。，2013年，第4916–4921页。

[21] M. Kamel、K. Alexis和R. Siegwart, "灵巧空中机械手的设计和建模"，在Proc。IEEE/RSJ Int. Conf. Intell。机器人系统。，2016年，第4870–4876页。

[22] T. W. Danko、K. P. Chaney和P. Y. Oh, "移动操作无人机的并联机械手"，在Proc。IEEE国际技术会议。实用机器人应用。，2015年，第1–6页。

[23] T. W. Danko和P. Y. Oh, "用于移动操作无人机的超冗余机械手"，在Proc。国际形态无人机。系统。，2013年，第974–981页。

[24] M. Kobilarov, "多体空中操纵器的非线性轨迹控制"，J. Intell。机器人系统。，2014年第73卷第1期第679–692页。

[25] K. Morton和L. F. G. Toro, "户外移动操纵无人机强健框架的开发"，在Proc。IEEE Aerosp。Conf.,2016年3月，第1–8页。

[26] V. Lippiello等人，"空中操纵分层任务组合的混合视觉伺服"，IEEE Robot。自动装置。莱特。，2016年1月，第1卷，第259–266页。

[27] C. Kanellakis、M.Terrran、D. Kominiak和G. Nikolakopoulos在Proc。第22届IEEE国际会议紧急会议。技术。工厂自动机。，2017年，第1–7页。

[28] A. Ollero等人，"aeroarms项目：具有先进的检查和维护操作能力的空中机器人"，IEEE Robot。自动装置。杂志，第25卷，第4期，第12–23页，2018年12月。

[29] D.Brescianni和R. D'Andrea, "全驱动多转子车辆的计算有效轨迹生成"，IEEE Trans。机器人第34卷第3期，第555–571页，2018年6月。

[30] M. Kamel等人，"voliro全方位六角直升机：一种灵活机动的可倾斜旋翼飞行器"，IEEE Robot。自动装置。杂志，第25卷，第4期，第34–44页，2018年12月。

[31] M. Tognon和A. Franchi, "带单向推进器的全方位飞行器：理论、优化设计和控制"，IEEE Robot。自动装置。莱特。，第3卷第3期，第2277–2282页，2018年7月。

[32] M、 Ryll等人，"空中机器人的6D交互控制：飞行末端效应器范例"，Int. J. Robot。Res.,第38卷，第9期，第1045–1062页，2019年。

[33] M. Orsag, C. Korpela, P. Oh和S. Bogdan,空中操纵。德国柏林：斯普林格，2018年。

[34] A. Suarez, F. Real, V. M. Vega, G. Heredia, A. Rodriguez Castaño和A. Ollero, "符合要求的双手空中操纵：标准和长距离配置"，IEEE Access,第8卷，88844–88865页，2020年5月。

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

[35] H. Paul, R. Miyazaki, R. Ladig, and K. Shimonomura, "Landing of a multirotor aerial vehicle on an uneven surface using multiple on-board manipulators," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2019, pp. 1926–1933.

[36] A. Suarez, G. Heredia, and A. Ollero, "Design of an anthropomorphic, compliant, and lightweight dual arm for aerial manipulation," *IEEE Access*, vol. 6, pp. 29173–29189, May 2018.

[37] A. Pumarola, A. Vakhitov, A. Agudo, F. Moreno-Noguer, and A. Sanfeliu, "Relative localization for aerial manipulation with PL-SLAM," in *Proc. Aerial Robot. Manipulation*, 2019, pp. 239–248.

[38] J. Paneque, J. R. Martinez-de Dios, and A. Ollero, "Multi-sensor 6-DoF localization for aerial robots in complex GNSS-denied environments," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2019, pp. 1978–1984.

[39] E. Mueggler, G. Gallego, H. Rebecq, and D. Scaramuzza, "Continuous-time visual-inertial odometry for event cameras," *IEEE Trans. Robot.*, vol. 34, no. 6, pp. 1425–1440, Dec. 2018.

[40] A. Santamaria-Navarro, P. Grosch, V. Lippiello, J. Solà, and J. Andrade-Cetto, "Uncalibrated visual servo for unmanned aerial manipulation," *IEEE/ASME Trans. Mechatronics*, vol. 22, no. 4, pp. 1610–1621, Aug. 2017.

[41] A. Caballero, M. Bejar, and A. Ollero, "On the use of velocity adaptation to outperform the motion planning with dynamics awareness in aerial long-reach manipulators with two arms," in *Proc. Int. Conf. Unmanned Aircr. Syst.*, Jun. 2018, pp. 1125–1133.

[42] A. Caballero *et al.*, "First experimental results on motion planning for transportation in aerial long-reach manipulators with two arms," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2018, pp. 8471–8477.

[43] A. Ollero and B. Siciliano, Eds. *Aerial Robotic Manipulation, (STAR Springer Tracts Adv. Robot. Series)*. Cham, Switzerland: Springer, Jul. 2019.

[44] M. A. Trujillo, J. R. Martinez-de Dios, C. Martin, A. Viguria, and A. Ollero, "Novel aerial manipulator for accurate and robust industrial NDT contact inspection: A new tool for the oil and gas inspection industry," *Sensors*, vol. 19, pp. 1–24, 2019.

[45] A. Flores-Abad, O. Ma, K. Pham, and S. Ulrich, "A review of space robotics technologies for on-orbit servicing," *Prog. Aerosp. Sci.*, vol. 68, pp. 1–26, 2014.

[46] I. Schjølberg and T. I Fossen, "Modelling and control of underwater vehicle-manipulator systems," in *Proc. rd Conf. Mar. Craft Maneuvering Control*. Citeseer, 1994, pp. 45–57.

[47] J. Yuh, "Design and control of autonomous underwater robots: A survey," *Auton. Robots*, vol. 8, no. 1, pp. 7–24, 2000.

[48] A. Suarez, V. M. Vega, M. Fernandez, G. Heredia, and A. Ollero, "Benchmarks for aerial manipulation," *IEEE Robot. Automat. Lett.*, vol. 5, no. 2, pp. 2650–2657, Apr. 2020.

[49] A. E. Jimenez-Cano, P. J. Sanchez-Cuevas, P. Grau, A. Ollero, and G. Heredia, "Contact-based bridge inspection multirotors: Design, modeling, and control considering the ceiling effect," *IEEE Robot. Automat. Lett.*, vol. 4, no. 4, pp. 3561–3568, Oct. 2019.

[50] M. Hamandi, F. Usai, Q. Sablé, N. Staub, M. Tognon, and A. Franchi, "Design of multirotor aerial vehicles: A taxonomy based on input allocation," 2021. [Online]. Available: https://hal.archives-ouvertes.fr/hal-02433405

[51] X. Meng, Y. He, and J. Han, "Survey on aerial manipulator: System, modeling, and control," *Robotica*, vol. 38, no. 7, pp. 1288–1317, 2020.

[52] F. Ruggiero, V. Lippiello, and A. Ollero, "Aerial manipulation: A literature review," *IEEE Robot. Automat. Lett.*, vol. 3, no. 3, pp. 1957–1964, Jul. 2018.

[53] A. Martín-Alcántara, P. Grau, R. Fernandez-Feria, and A. Ollero, "A simple model for gliding and low-amplitude flapping flight of a bio-inspired UAV," in *Proc. Int. Conf. Unmanned Aircr. Syst.*, 2019, pp. 729–737.

[54] A. Suarez , P. Grau, G. Heredia, and A. Ollero, "Winged aerial manipulation robot with dual arm and tail," *Appl. Sci.*, vol. 10, no. 14, pp. pp. 1–19, 2020.

[55] A. Franchi, R. Carli, D. Bicego, and M. Ryll, "Full-pose tracking control for aerial robotic systems with laterally-bounded input force," *IEEE Trans. Robot.*, vol. 34, no. 2, pp. 534–541, Apr. 2018.

[56] M. Ryll, H. H. Bülthoff, and P. R. Giordano, "A novel overactuated quadrotor unmanned aerial vehicle: Modeling, control, and experimental validation," *IEEE Trans. Control Syst. Technol.*, vol. 23, no. 2, pp. 540–556, Mar. 2015.

[57] A. De Luca and G. Oriolo, "Trajectory planning and control for planar robots with passive last joint," *Int. J. Robot. Res.*, vol. 21, no. 5/6, pp. 575–590, 2002.

[58] H. Yang and D. J. Lee, "Dynamics and control of quadrotor with robotic manipulator," in *Proc. IEEE Int. Conf. Robot. Automat.*, Hong Kong, 2014, pp. 5544–5549.

[59] J. Welde, J. Paulos, and V. Kumar, "Dynamically feasible task space planning for underactuated aerial manipulators," *IEEE Robot. Automat. Lett.*, vol. 6, no. 2, pp. 3232–3239, Apr. 2021.

[60] H. Nguyen and D. Lee, "Hybrid force/motion control and internal dynamics of quadrotors for tool operation," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Tokyo, Japan, 2013, pp. 3458–3464.

[61] B. Yüksel, G. Buondonno, and A. Franchi, "Differential flatness and control of protocentric aerial manipulators with any number of arms and mixed rigid-/elastic-joints," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Daejeon, South Korea, 2016, pp. 561–566.

[62] D. Bicego, J. Mazzetto, M. Farina, R. Carli, and A. Franchi, "Nonlinear model predictive control with actuator constraints for multi-rotor aerial vehicles," *J. Intell. Robot. Syst.*, vol. 3, no. 100, pp. 1213–1247, 2020.

[63] M. Fumagalli, R. Naldi, A. Macchelli, R. Carloni, S. Stramigioli, and L. Marconi, "Modeling and control of a flying robot for contact inspection," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2012, pp. 3532–3537.

[64] F. Forte, R. Naldi, A. Macchelli, and L. Marconi, "Impedance control of an aerial manipulator," in *Proc. Amer. Control Conf.*, 2012, pp. 3839–3844.

[65] V. Lippiello and F. Ruggiero, "Exploiting redundancy in Cartesian impedance control of UAVs equipped with a robotic arm," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Vilamoura, Portugal, 2012, pp. 3768–3773.

[66] M. Tognon *et al.*, "A truly redundant aerial manipulator system with application to push-and-slide inspection in industrial plants," *IEEE Robot. Automat. Lett.*, vol. 4, no. 2, pp. 1846–1851, Apr. 2019.

[67] J. L. J. Scholten, M. Fumagalli, S. Stramigioli, and R. Carloni, "Interaction control of an uav endowed with a manipulator," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2013, pp. 4910–4915.

[68] V. Lippiello, G. A. Fontanelli, and F. Ruggiero, "Image-based visual-impedance control of a dual-arm aerial manipulator," *IEEE Robot. Automat. Lett.*, vol. 3, no. 3, pp. 1856–1863, Jul. 2018.

[69] A. Suarez, G. Heredia, and A. Ollero, "Physical-virtual impedance control in ultralightweight and compliant dual-arm aerial manipulators," *IEEE Robot. Automat. Lett.*, vol. 3, no. 3, pp. 2553–2560, Jul. 2018.

[70] G. Antonelli *et al.*, "Impedance control of an aerial-manipulator: Preliminary results," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Daejeon, South Korea, 2016, pp. 3848–3853.

[71] F. Ruggiero, J. Cacace, H. Sadeghian, and V. Lippiello, "Impedance control of VToL UAVs with a momentum-based external generalized forces estimator," in *Proc. IEEE Int. Conf. Robot. Automat.*, Hong Kong, 2014, pp. 2093–2099.

[72] M. Tognon, C. Gabellieri, L. Pallottino, and A. Franchi, "Aerial co-manipulation with cables: The role of internal force for equilibria, stability, and passivity," *IEEE Robot. Automat. Lett., Special Issue Aerial Manipulation*, vol. 3, no. 3, pp. 2577–2583, Jul. 2018.

[73] C. Gabellieri, M. Tognon, D. Sanalitro, L. Palottino, and A. Franchi, "A. study on force-based collaboration in swarms," *Swarm Intell.*, vol. 14, pp. 57–82, 2020.

[74] F. Augugliaro and R. D'Andrea, "Admittance control for physical human-quadrocopter interaction," in *Proc. 12th Eur. Control Conf.*, Zürich, Switzerland, 2013, pp. 1805–1810.

[75] G. Heredia *et al.*, "Control of a multirotor outdoor aerial manipulator," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2014, pp. 3417–3422.

[76] B. Yüksel, C. Secchi, H. H. Bülthoff, and A. Franchi, "Aerial physical interaction via IDA-PBC," *Int. J. Robot. Res.*, vol. 38, no. 4, 2019, Art. no. 403421.

[77] R. Rashad, J. B. C. Engelen, and S. Stramigioli, "Energy tank-based wrench/impedance control of a fully-actuated hexarotor: A geometric port-Hamiltonian approach," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2019, pp. 6418–6424.

[78] M. Tognon, S. S. Dash, and A. Franchi, "Observer-based control of position and tension for an aerial robot tethered to a moving platform," *IEEE Robot. Automat. Lett.*, vol. 1, no. 2, pp. 732–737, Jul. 2016.

[79] M. Tognon and A. Franchi, "Dynamics, control, and estimation for aerial robots tethered by cables or bars," *IEEE Trans. Robot.*, vol. 33, no. 4, pp. 834–845, Aug. 2017.

[80] M. Tognon and A. Franchi, *Theory and Applications for Control of Aerial Robots in Physical Interaction Through Tethers, Springer Tracts Adv. Robot.*, Cham, Switzerland: Springer, 2020.

这篇文章已被接受收录在本刊未来的一期中。除分页外，内容均为最终内容。

[35] H. Paul、R. Miyazaki、R. Ladig和K. Shimonomura, "使用多个机载操纵器将多旋翼飞行器降落在不平的表面上"，在Proc。IEEE/RSJ Int. Conf. Intell。机器人系统。，2019年，第1926–1933页。

[36] A. Suarez、G. Heredia和A. Ollero, "用于空中操纵的拟人、柔顺和轻质双臂的设计"，IEEE Access,第6卷，第29173–29189页，2018年5月。

[37] A. Pumarola 、 A. Vakhitov 、 A. Agudo 、 F. Moreno Noguer 和 A.Sanfeliu,"PL-SLAM空中操纵的相对定位"，在Proc。空中机器人。《操纵》，2019年，第239–248页。

[38] J. Paneque、J. R. Martinez de Dios和A. Ollero, "复杂GNSS环境中空中机器人的多传感器6自由度定位"，在Proc。IEEE/RSJ Int. Conf. Intell。机器人系统。，2019年，1978–1984页。

[39] E. Mueggler, G. Gallego, H. Rebecq和D. Scaramuzza, "事件摄像机的连续时间视觉惯性里程计"，IEEE Trans。机器人第34卷第6期，第1425–1440页，2018年12月。

[40] A. Santamaria Navarro，P.Grosch,V.Lippiello,J.Solá和J. Andrade- Cetto, "无人机操纵的未校准视觉伺服"，IEEE/ASME Trans。《机电一体化》，第22卷，第4期，第1610–1621页，2017年8月。

[41] A. Caballero、M. Bejar和A. Ollero, "关于在双臂空中长距离机械手中使用速度自适应来超越具有动力学感知的运动规划"，在Proc。国际形态无人机。系统。，2018年6月，第1125–1133页。

[42] A. Caballero等人，"双臂空中长距离机械手运输运动规划的首次实验结果"，在Proc。IEEE/RSJ Int. Conf. Intell。机器人系统。，2018年，第8471–8477页。

[43] A. Ollero和B. Siciliano编辑：《空中机器人操作》（STAR Springer Tracts Adv. Robot.系列）。瑞士湛：2019年7月，斯普林格。

[44] M. A. Trujillo、J. R. Martinez de Dios、C. Martin、A. Viguria和A. Ollero, "用于精确和稳健工业无损检测接触检测的新型空中机械手：油气检测行业的新工具"，传感器，第19卷，第1–24页，2019年。

[45] A. Flores Abad、O. Ma、K. Pham和S. Ulrich, "用于在轨服务的空间机器人技术综述"，Prog。Aerosp。Sci。，2014年第68卷第1–26页。

[46] I. Schjølberg和T. I Fossen, "水下航行器机械手系统的建模和控制"，在Proc。3月第三次形态，飞行器操纵控制。Citeseer, 1994年，第45–57页。

[47] J. Yuh, "自主水下机器人的设计和控制：综述，" 奥顿。《机器人》，第8卷，第一期，第7–24页，2000年。

[48] A. Suarez、V. M. Vega、M. Fernandez、G. Heredia和A. Ollero,《空中操纵基准》，IEEE Robot。自动装置。莱特。，第5卷第2期，第2650–2657页，2020年4月。

[49] A. E. Jimenez Cano、P. J. Sanchez Cuevas、P. Grau、A. Ollero和G. Heredia, "基于接触的桥梁检测多转子：考虑天花板效应的设计、建模和控制"，IEEE Robot。自动装置。莱特。，第4卷第4期，第3561–3568页，2019年10月。

[50] M. Hamandi, F. Usai, Q. Sablé, N. Staub, M. Tognon和A. Franchi, "多旋翼飞行器的设计：基于输入分配的分类法"- cation," 2021. [Online]. Available: https://hal.archives-ouvertes.fr/hal- 02433405

[51] 孟X，何Y，韩J，"空中机械手的研究概况：系统、建模和控制"，机器人学，第38卷，第7期，1288–1317页，2020年。

[52] F. Ruggiero、V. Lippiello和A. Ollero, "空中操纵：文献综述"，IEEE机器人。自动装置。莱特。，第3卷第3期，1957–1964页，2018年7月。

[53] A. Martín-Alcántara、P. Grau、R. Fernandez Feria和A. Ollero, "仿生无人机滑翔和低振幅扑翼飞行的简单模型"，在Proc。国际形态无人机。系统。，2019年，第729–737页。

[54] A. Suarez、P. Grau、G. Heredia和A. Ollero, "带双臂和尾巴的有翼空中操纵机器人",应用。Sci。, 2020年第10卷第14期第1–19页。

[55] A. Franchi, R. Carli, D. Bicego和M. Ryl，"具有横向有界输入力的空中机器人系统的全姿态跟踪控制"，IEEE Trans。机器人2018年4月，第34卷第2期，第534–541页。

[56] M. Ryll、H. H. Bülthoff和P. R. Giordano, "新型过驱动四旋翼无人机：建模、控制和实验验证"，IEEE Trans。控制系统。技术。，第23卷第2期，第540–556页，2015年3月。

[57] A. De Luca和G. Oriolo, "带有被动最后关节的平面机器人的轨迹规划和控制"，Int. J. Robot。《自然资源法》，第21卷，第5/6号，第575–590页，2002年。

[58] H. Yang和D. J. Lee, "机械手四旋翼的动力学和控制"，在Proc。IEEE内部配置机器人。自动装置。，香港，2014年，第5544–5549页。

[59] J. Welde, J. Paulos和V. Kumar, "欠驱动空中机械手的动态可行任务空间规划"，IEEE Robot。自动装置。莱特。，第6卷，第2期，第3232–3239页，2021 4月。

[60] H. Nguyen和D. Lee, "用于刀具操作的四转子的混合力/运动控制和内部动力学"，在Proc。IEEE/RSJ Int. Conf. Intell。机器人系统。，日本东京，2013年，第3458–3464页。

[61] B. Yüksel, G. Buondonno和A. Franchi, "具有任意数量臂和混合刚性/弹性关节的原始中心空中机械手的微分平面度和控制"，在Proc。IEEE/RSJ Int. Conf. Intell。机器人系统。，韩国大田，2016年，第561–566页。

[62] D. Bicego, J. Mazzetto, M. Farina, R. Carli和A. Franchi, "多旋翼飞行器带执行器约束的非线性模型预测控制"，J. Intell。机器人系统。，第三卷，第100期，第1213–1247页，2020年。

[63] M. Fumagalli、R. Naldi、A. Macchelli、R. Carloni、S. Stramigioli和L. Marconi, "用于接触检查的飞行机器人的建模和控制"，在Proc。IEEE/RSJ Int. Conf. Intell。机器人系统。，2012年，第3532–3537页。

[64] F. Forte、R. Naldi、A. Macchelli和L. Marconi, "空中机械手的阻抗控制"，在Proc。艾默尔。《控制形态》，2012年，第3839–3844页。

[65] V. Lippiello和F. Ruggiero, "利用配备机械臂的无人机笛卡尔阻抗控制中的冗余"，在Proc。IEEE/RSJ Int. Conf. Intell。机器人系统。，葡萄牙维拉穆拉，2012年，第3768–3773页。

[66] M. Tognon等人，"一个真正冗余的空中机械手系统，应用于工业工厂的推送和滑动检查"，IEEE Robot。自动装置。莱特。，第4卷第2期，1846–1851页，2019年4月。

[67] J. L. J. Scholten、M. Fumagalli、S. Stramigioli和R. Carloni, "配备机械手的无人机的交互控制"，在Proc。IEEE内部配置机器人。自动装置。，2013年，第4910–4915页。

[68] V. Lippiello, G. A. Fontanelli和F. Ruggiero, "双臂空中机械手基于图像的视觉阻抗控制"，IEEE Robot。自动装置。莱特。，第3卷第3期，1856–1863页，2018年7月。

[69] A. Suarez、G. Heredia和A. Ollero, "超轻量柔性双臂空中机器人中的物理虚拟阻抗控制"，IEEE Robot。自动装置。莱特。，2018年7月，第3卷第3期，第2553–2560页。

[70] G. Antonelli等人，"空中机械手的阻抗控制：初步结果"，在Proc。IEEE/RSJ Int. Conf. Intell。机器人系统。，韩国大田，2016年，第3848–3853页。

[71] F. Ruggiero, J. Cacace, H. Sadeghian和V. Lippiello, "基于动量的外部广义力估计器的垂直起降无人机阻抗控制"，在Proc。IEEE内部配置机器人。自动装置。，香港，2014年，第2093–2099页。

[72] M. Tognon、C. Gabelli、L. Pallottino和A. Franchi, "与电缆的空中协同操纵：平衡、稳定性和被动性的内力作用"，IEEE Robot。自动装置。莱特。，《空中操纵》特刊，第3卷，第3期，第2577-25832018年7月。

[73] C. Gabellieri、M. Tognon、D. Sanalitro、L. Palottino和A. Franchi, "A.群体中基于力量的协作研究"，Swarm Intell。，第14卷，第57–82页，2020年。

[74] F.Auguliaro和R.D'Andrea，"人体物理交互的准入控制——四机器人互动"，在Proc。12欧元。《控制形态》，苏黎世，瑞士，2013年，第1805–1810页。

[75] G. Heredia等人，"多转子室外空中机械手的控制"，在Proc。IEEE/RSJ Int. Conf. Intell。机器人系统。，2014年，第3417–3422页。

[76] B. Yüksel、C. Secchi、H. H. Bülthoff和A. Franchi, "通过IDA-PBC进行空中物理交互"，Int. J. Robot。第38卷，第4期，2019年，第。403421号。

[77] R. Rashad、J. B. C. Engelen和S. Stramigioli, "基于能量罐的全驱动六旋翼扳手/阻抗控制：几何端口哈密顿方法"，在Proc。内部形态机器人。自动装置。，2019年，第6418–6424页。

[78] M. Tognon、S. S. Dash和A. Franchi, "固定在移动平台上的空中机器人基于观测器的位置和张力控制"，IEEE Robot。自动装置。莱特。，2016年7月，第1卷第2期，第732–737页。

[79] M. Tognon和A. Franchi, "电缆或杆系空中机器人的动力学、控制和评估"，IEEE Trans。机器人2017年8月，第33卷第4期，第834–845页。

[80] M. Tognon和A. Franchi,《通过绳索进行物理交互的空中机器人控制理论与应用》，Springer Tracts Adv. Robot。，瑞士湛：斯普林格，2020年。

[81] S. Park *et al.*, "ODAR: Aerial manipulation platform enabling omnidirectional wrench generation," *IEEE/ASME Trans. Mechatronics*, vol. 23, no. 4, pp. 1907–1918, Aug. 2018.

[82] G. Nava, Q. Sablé, M. Tognon, D. Pucci, and A. Franchi, "Direct force feedback control and online multi-task optimization for aerial manipulators," *IEEE Robot. Automat. Lett.*, vol. 5, no. 2, pp. 331–338, Apr. 2020.

[83] S. Kim, S. Choi, and H. J. Kim, "Aerial manipulation using a quadrotor with a two DOF robotic arm," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2013, pp. 4990–4995.

[84] H. Seo, S. Kim, and H. J. Kim, "Aerial grasping of cylindrical object using visual servoing based on stochastic model predictive control," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2017, pp. 6362–6368.

[85] S. Hamaza *et al.*, "Sensor installation and retrieval operations using an unmanned aerial manipulator," *IEEE Robot. Automat. Lett.*, vol. 4, no. 3, pp. 2793–2800, Jul. 2019.

[86] K. Bodie *et al.*, "Active interaction force control for contact-based inspection with a fully actuated aerial vehicle," *IEEE Trans. Robot.*, early access, Dec. 15, 2020, doi: 10.1109/TRO.2020.3036623.

[87] K. Bodie *et al.*, "An omnidirectional aerial manipulation platform for contact-based inspection," in *Proc. Robotics: Sci. Syst.*, 2019, pp. 1–9.

[88] M. Orsag, C. Korpela, S. Bogdan, and P. Oh, "Valve turning using a dual-arm aerial manipulator," in *Proc. Int. Conf. Unmanned Aircr. Syst.*, 2014, pp. 836–841.

[89] R. Cano, C. Pérez, F. O. Pruaño, A. Ollero, and G. Heredia, "Mechanical design of a 6-DOF aerial manipulator for assembling bar structures using UAVs," in Proc. 2nd RED-UAS, 2014.

[90] K. Steich, M. Kamel, P. Beardsley, M. K. Obrist, R. Siegwart, and T. Lachat, "Tree cavity inspection using aerial robots," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2016, pp. 4856–4862.

[91] P. Chermprayong, K. Zhang, F. Xiao, and M. Kovac, "An integrated delta manipulator for aerial repair: A new aerial robotic system," *IEEE Robot. Automat. Mag.*, vol. 26, no. 1, pp. 54–66, Mar. 2019.

[92] R. Naldi, A. Macchelli, N. Mimmo, and L. Marconi, "Robust control of an aerial manipulator interacting with the environment," *IFAC-PapersOnLine*, vol. 51, no. 13, pp. 537–542, 2018.

[93] H. W. Wopereis, J. J. Hoekstra, T. H. Post, G. A Folkertsma, S. Stramigioli, and M. Fumagalli, "Application of substantial and sustained force to vertical surfaces using a quadrotor," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2017, pp. 2704–2709.

[94] K. Alexis, G. Darivianakis, M. Burri, and R. Siegwart, "Aerial robotic contact-based inspection: Planning and control," *Auton. Robots*, vol. 40, no. 4, pp. 631–655, 2016.

[95] I. Palunko, P. Cruz, and R. Fierro, "Agile load transportation: Safe and efficient load manipulation with aerial robots," *IEEE Robot. Automat. Mag.*, vol. 19, no. 3, pp. 69–79, Sep. 2012.

[96] I. Palunko, A. Faust, P. Cruz, L. Tapia, and R. Fierro, "A. reinforcement learning approach towards autonomous suspended load manipulation using aerial robots," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2013, pp. 4896–4901.

[97] K. Sreenath, N. Michael, and V. Kumar, "Trajectory generation and control of a quadrotor with a cable-suspended load-a differentially-flat hybrid system," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2013, pp. 4888–4895.

[98] P. Foehn, D. Falanga, N. Kuppuswamy, R. Tedrake, and D. Scaramuzza, "Fast trajectory optimization for agile quadrotor maneuvers with a cable-suspended payload," in *Proc. Robotics: Sci. Syst.*, 2017, pp. 1–10.

[99] F. Augugliaro, A. Mirjan, F. Gramazio, M. Kohler, and R. D'Andrea, "Building tensile structures with flying machines," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2013, pp. 3487–3492.

[100] N. Staub, D. Bicego, Q. Sablé, V. Arellano-Quintana, S. Mishra, and A. Franchi, "Towards a flying assistant paradigm: The OTHex," in *Proc. IEEE Int. Conf. Robot. Automat.*, Brisbane, QL, Australia, 2018, pp. 6997–7002.

[101] N. Staub *et al.*, "The tele-MAGMaS: An aerial-ground comanipulator system," *IEEE Robot. Automat. Mag.*, vol. 25, no. 4, pp. 66–75, Dec. 2018.

[102] A. Nikou, G. C. Gavridis, and K. J. Kyriakopoulos, "Mechanical design, modelling and control of a novel aerial manipulator," in *Proc. IEEE Int. Conf. Robot. Automat.*, Seattle, WA, USA, 2015, pp. 4698–4703.

[103] C. Papachristos, K. Alexis, and A. Tzes, "Dual-authority thrust-vectoring of a tri-tiltrotor employing model predictive control," *J. Intell. Robot. Syst.*, vol. 81, no. 3/4, pp. 471–504, 2016.

[104] T. Anzai, M. Zhao, S. Nozawa, F. Shi, K. Okada, and M. Inaba, "Aerial grasping based on shape adaptive transformation by halo: Horizontal plane transformable aerial robot with closed-loop multilinks structure," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2018, pp. 6990–6996.

[105] M. Zhao, K. Kawasaki, X. Chen, S. Noda, K. Okada, and M. Inaba, "Whole-body aerial manipulation by transformable multirotor with two-dimensional multilinks," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2017, pp. 5175–5182.

[106] M. Zhao, F. Shi, T. Anzai, K. Okada, and M. Inaba, "Online motion planning for deforming maneuvering and manipulation by multilinked aerial robot based on differential kinematics," *IEEE Robot. Automat. Lett.*, vol. 5, no. 2, pp. 1602–1609, Apr. 2020.

[107] R. Naldi, A. Ricco, A. Serrani, and L. Marconi, "A modular aerial vehicle with redundant actuation," in *Proc. Int. Conf. Intell. Robots Syst.*, 2013, pp. 1393–1398.

[108] D. Sanalitro, H. J. Savino, M. Tognon, J. Cortés, and A. Franchi, "Full-pose manipulation control of a cable-suspended load with multiple UAVs under uncertainties," *IEEE Robot. Automat. Lett.*, vol. 5, no. 2, pp. 2185–2191, Apr. 2020.

[109] H. Yang, S. Park, J. Lee, J. Ahn, D. Son, and D. Lee, "LASDRA: Large-size aerial skeleton system with distributed rotor actuation," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2018, pp. 7017–7023.

[110] C. Korpela, P. Brahmbhatt, M. Orsag, and P. Oh, "Towards the realization of mobile manipulating unmanned aerial vehicles (MM-UAV): Peg-in-hole insertion tasks," in *Proc. IEEE Conf. Technol. Practical Robot Appl.*, Apr. 2013, pp. 1–6.

[111] Y. Sarkisov *et al.*, "Development of SAM: Cable-suspended aerial manipulator," in *Proc. IEEE Int. Conf. Robot. Automat.*, Montreal, QC, Canada, 2019, pp. 5323–5329.

[112] G. Garimella and M. Kobilarov, "Towards model-predictive control for aerial pick-and-place," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2015, pp. 4692–4697.

[113] T. Bartelds, A. Capra, S. Hamaza, S. Stramigioli, and M. Fumagalli, "Compliant aerial manipulators: Toward a new generation of aerial robotic workers," *IEEE Robot. Automat. Lett.*, vol. 1, no. 1, pp. 477–483, Jan. 2016.

[114] S. Kim, H. Seo, and H. J. Kim, "Operating an unknown drawer using an aerial manipulator," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2015, pp. 5503–5508.

[115] D. Falanga, K. Kleber, S. Mintchev, D. Floreano, and D. Scaramuzza, "The foldable drone: A morphing quadrotor that can squeeze and fly," *IEEE Robot. Automat. Lett.*, vol. 4, no. 2, pp. 209–216, Apr. 2019.

[116] M. Zhao *et al.*, "Flight motion of passing through small opening by dragon: Transformable multilinked aerial robot," in *Proc. Int. Conf. Intell. Robots Syst.*, 2018, pp. 4735–4742.

[117] T. Anzai, M. Zhao, M. Murooka, F. Shi, K. Okada, and M. Inaba, "Design, modeling and control of fully actuated 2D transformable aerial robot with 1 DoF thrust vectorable link module," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2019, pp. 2820–2826.

[118] B. Yüksel, S. Mahboubi, C. Secchi, H. H. Bülthoff, and A. Franchi, "Design, identification and experimental testing of a light-weight flexible-joint arm for aerial physical interaction," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2015, pp. 870–876.

[119] C. D. Bellicoso, L. R. Buonocore, V. Lippiello, and B. Siciliano, "Design, modeling and control of a 5-DoF light-weight robot arm for aerial manipulation," in *Proc. 23rd Mediterranean Conf. Control Automat.*, 2015, pp. 853–858.

[120] A. Suarez, A. E. Jimenez-Cano, V. M. Vega, G. Heredia, A. Rodriguez-Castaño, and A. Ollero, "Design of a lightweight dual arm system for aerial manipulation," *Mechatronics*, vol. 50, pp. 30–44, 2018.

[121] A. Suarez, P. Sanchez-Cuevas, M. Fernandez, M. Perez, G. Heredia, and A. Ollero, "Lightweight and compliant long reach aerial manipulator for inspection operations," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2018, pp. 6746–6752.

[122] F. Ruggiero *et al.*, "A multilayer control for multirotor UAVs equipped with a servo robot arm," in *Proc. IEEE Int. Conf. Robot. Automat.*, Seattle, WA, USA, 2015, pp. 4014–4020.

[123] A. Suarez, G. Heredia, and A. Ollero, "Lightweight compliant arm with compliant finger for aerial manipulation and inspection," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2016, pp. 4449–4454.

[124] A Suarez, A. M. Giordano, K. Kondak, G. Heredia, and A. Ollero, "Flexible link long reach manipulator with lightweight dual arm: Soft-collision detection, reaction, and obstacle localization," in *Proc. IEEE Int. Conf. Soft Robot.*, 2018, pp. 406–411.

[125] A. Suarez, G. Heredia, and A. Ollero, "Lightweight compliant arm for aerial manipulation," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2015, pp. 1627–1632.

[126] A. Y. Mersha, S. Stramigioli, and R. Carloni, "On bilateral teleoperation of aerial robots," *IEEE Trans. Robot.*, vol. 30, no. 1, pp. 258–274, Feb. 2014.

[81] S. Park等人，“ODAR：实现全方位扳手生成的空中操纵平台”，IEEE/ASME Trans。《机电一体化》，第23卷，第4期，第1907–1918页，2018年8月。

[82] G. Nava, Q. Sablé, M. Tognon, D. Pucci和A. Franchi, “空中机械手的直接力反馈控制和在线多任务优化”，IEEE Robot。自动装置。莱特。，第5卷第2期，第331–338页，2020年4月。

[83] S. Kim、S. Choi和H. J. Kim, “使用带有两个自由度机械臂的四旋翼进行空中操纵”，在Proc。IEEE/RSJ Int. Conf. Intell。机器人系统。，2013年，第4990–4995页。

[84] H. Seo、S. Kim和H. J. Kim, “基于随机模型预测控制的视觉伺服对圆柱形物体的空中抓取”，在Proc。IEEE内部配置机器人。自动装置。，2017年，第6362–6368页。

[85] S. Hamaza等人，“使用无人机的传感器安装和检索操作”，IEEE Robot。自动装置。莱特。，第4卷第3期，第2793–2800页，2019年7月。

[86] K. Bodie等人，“全驱动飞行器接触式检测的主动交互力控制”，IEEE Trans。机器人早访问，2020年12月15日，内政部：10.1109/TRO.2020.3036623.

[87] K. Bodie等人，“用于接触式检查的全方位空中操纵平台”，在Proc。机器人学：Sci。系统。，2019年，第1–9页。

[88] M. Orsag、C. Korpela、S. Bogdan和P. Oh, “使用双臂空中机械手转动阀门”，在Proc。国际形态无人机。系统。，2014年，第836–841页。

[89] R. Cano、C. Pérez、F. O. Pruaño、A. Ollero和G. Heredia, “使用无人机组装杆结构的6自由度空中机械手的机械设计”，在Proc。第二届RED-UAS, 2014年。

[90] K. Steich、M. Kamel、P. Beardsley、M. K. Obrist、R. Siegwart和T. Lachat, “使用空中机器人检查树洞”，在Proc。IEEE/RSJ Int. Conf. Intell。机器人系统。，2016年，第4856–4862页。

[91] P. Chermprayong、K. Zhang、F. Xiao和M. Kovac, “用于空中维修的集成delta机械手：一种新的空中机器人系统”，IEEE Robot。自动装置。杂志，第26卷，第一期，第54–66页，2019年3月。

[92] R. Naldi、A. Macchelli、N. Mimmo和L. Marconi, “与环境相互作用的空中机械手的鲁棒控制”，IFAC- PapersOnLine,第51卷，第13期，第537–542页，2018年。

[93] H. W. Wopereis、J. J. Hoekstra、T. H. Post、G. A Folkertsma、S. Strami- gioli和M. Fumagalli, “使用四旋翼向垂直表面施加巨大且持续的力”，在Proc。IEEE内部配置机器人。自动装置。，2017年，第2704–2709页。

[94] K. Alexis、G.Darivanakis、M. Burri和R. Siegwart, “基于空中机器人接触的检查：规划和控制”，Auton。《机器人》，第40卷，第4期，第631–655页，2016年。

[95] I. Palunko、P. Cruz和R. Fierro, “敏捷负载运输：使用空中机器人进行安全高效的负载操纵”，IEEE Robot。自动装置。杂志，第19卷，第3期，第69–79页，2012年9月。

[96] I. Palunko、A. Faust、P. Cruz、L. Tapia和R. Fierro, “A.使用空中机器人实现自动悬浮物操纵的强化学习方法”，在Proc。IEEE内部配置机器人。自动装置。，2013年，第4896–4901页。

[97] K. Sreenath, N. Michael和V. Kumar, “带缆索悬浮负载的四旋翼轨迹生成和控制——一种差分扁平混合动力系统”，在Proc。IEEE内部配置机器人。自动装置。，2013年，第4888–4895页。

[98] P. Foehn, D. Falanga, N. Kuppuswamy, R. Tedrake和D. Scaramuzza, “具有缆索悬挂有效载荷的敏捷四旋翼机动的快速轨迹优化”，在Proc。机器人学：Sci。系统。，2017年，第1–10页。

[99] F.Auguliaro、A. Mirjan、F. Gramazio、M. Kohler和R.D'Andrea，“用飞行器建造张力结构”，在Proc。IEEE/RSJ Int. Conf. Intell。机器人系统。，2013年，第3487–3492页。

[100] N.斯塔布、D.比塞戈、Q.萨布雷、V.阿雷亚诺·昆塔纳、S.米什拉和
A. Franchi, “走向飞行助手范例：奥赛克斯”，在Proc。IEEE内部配置机器人。自动装置。，澳大利亚昆士兰布里斯班，2018年，第6997–7002页。

[101] N. Staub等人，“远程岩浆：空中地面操作系统”，IEEE Robot。自动装置。杂志，第25卷，第4期，第66–75页，2018年12月。

[102] A. Nikou、G. C. Gavridis和K. J. Kyriakopoulos, “新型空中机械手的机械设计、建模和控制”，在Proc。IEEE内部配置机器人。自动装置。，美国华盛顿州西雅图，2015年，第4698–4703页。

[103] C. Papachristos, K. Alexis和A. Tzes, “采用模型预测控制的三倾转旋翼双权限推力矢量控制”，J. Intell。机器人系统。，第81卷，第3/4号，第471–504页，2016年。

[104] T. Anzai, M. Zhao, S. Nozawa, F. Shi, K. Okada和M. Inaba, “基于halo形状自适应变换的空中抓取：具有闭环多线结构的水平面可变换空中机器人”，在Proc。IEEE内部配置机器人。自动装置。，2018年，第6990–6996页。

[105] M. Zhao, K. Kawasaki, X. Chen, S. Noda, K. Okada和M. Inaba, “具有二维多线的可变换多旋翼的全身空中操纵”，在Proc。IEEE内部配置机器人。自动装置。，2017年，第5175–5182页。

[106] M. Zhao, F. Shi, T. Anzai, K. Okada和M. Inaba, “基于微分运动学的多链空中机器人变形机动和操纵的在线运动规划”，IEEE Robot。自动装置。莱特。，第5卷第2期，第1602–1609页，2020年4月。

[107] R. Naldi、A. Ricco、A. Serrani和L. Marconi, “具有冗余驱动的模块化飞行器”，在Proc。内特形态内特。机器人系统。，2013年，第1393–1398页。

[108] D. Sanalitro、H. J. Savino、M. Tognon、J. Cortés和A. Franchi, “不确定性下多无人机悬索负载的全姿态操纵控制”，IEEE Robot。自动装置。莱特。，2020年4月，第5卷第2期，第2185–2191页。

[109] H. Yang, S. Park, J. Lee, J. Ahn, D. Son和D. Lee, “LASDRA：具有分布式转子驱动的大型空中骨架系统”，在Proc。IEEE内部配置机器人。自动装置。，2018年，第7017–7023页。

[110] C. Korpela, P. Brahmbhatt, M. Orsag和P. Oh, “实现移动操纵无人机（MM-UAV）：钉孔插入任务”，在Proc。IEEE Conf. Technol。实用机器人应用。，2013年4月，第1–6页。

[111] Y. Sarkisov等人，“SAM的发展：悬索式空中操纵器”，在Proc。IEEE内部配置机器人。自动装置。，加拿大魁北克省蒙特利尔，2019年，第5323–5329页。

[112] G. Garimella和M. Kobilarov, “空中拾取和放置的模型预测控制”，在Proc。IEEE内部配置机器人。自动装置。，2015年，第4692–4697页。

[113] T. Bartelds、A. Capra、S. Hamaza、S. Stramigioli和M. Fumagalli, “顺应式空中机械手：迈向新一代空中机器人工人”，IEEE Robot。自动装置。莱特。，2016年1月，第1卷，第477–483页。

[114] S. Kim、H. Seo和H. J. Kim, “使用空中操纵器操作一个未知的抽屉”，在Proc。IEEE内部配置机器人。自动装置。，2015年，第5503–5508页。

[115] D. Falanga、K. Kleber、S. Mintchev、D. Floreano和D. Scaramuzza, “可折叠无人机：可以挤压和飞行的变形四旋翼”，IEEE机器人。自动装置。莱特。，第4卷，第2期，第209–216页，2019年4月。

[116] M. Zhao等人，“龙穿过小开口的飞行运动：可变形多链空中机器人”，在Proc。内特形态内特。机器人系统。，2018年，第4735–4742页。

[117] T、 Anzai, M. Zhao, M. Murooka, F. Shi, K. Okada和M. Inaba, “带1个自由度推力矢量连杆模块的全驱动2D可变换空中机器人的设计、建模和控制”，过程中。IEEE/RSJ Int. Conf. Intell。机器人系统。，2019年，第2820–2826页。

[118] B. Yüksel、S. Mahboubi、C. Secchi、H. H. Bülthoff和A. Franchi, “用于空中物理交互的轻型柔性关节臂的设计、识别和实验测试”，在Proc。IEEE内部配置机器人。自动装置。，2015年，第870–876页。

[119] C. D. Bellicoso、L. R. Buonocore、V. Lippiello和B. Siciliano, “用于空中操纵的5自由度轻型机械臂的设计、建模和控制”，在Proc。23地中海形态控制自动机。，2015年，第853–858页。

[120] A. Suarez、A. E. Jimenez Cano、V. M. Vega、G. Heredia、A. Rodriguez- Castaño和A. Ollero, “空中操纵用轻型双臂系统的设计”，机电一体化，第50卷，第30–44页，2018年。

[121] A.苏亚雷斯、P.桑切斯·库瓦斯、M.费尔南德斯、M.佩雷斯、G.埃雷迪亚和
A. Ollero, “用于检查操作的轻型且符合要求的长距离空中机械手”，在Proc。IEEE/RSJ Int. Conf. Intell。机器人系统。，2018年，第6746–6752页。

[122] F. Ruggiero等人，“配备伺服机械臂的多旋翼无人机的多层控制”，在Proc。IEEE内部配置机器人。自动装置。，美国华盛顿州西雅图，2015年，第4014–4020页。

[123] A. Suarez、G. Heredia和A. Ollero在Proc.中的“带有柔顺手指的轻型柔顺手臂，用于空中操纵和检查”。IEEE/RSJ Int. Conf. Intell。机器人系统。，2016年，第4449–4454页。

[124] A.Suarez、A. M. Giordano、K. Kondak、G. Heredia和A. Ollero, “具有轻型双臂的柔性连杆长距离机械手：软碰撞检测、反应和障碍物定位”，在Proc。IEEE Int. Conf.软机器人。，2018年，第406–411页。

[125] A. Suarez、G. Heredia和A. Ollero,《空中操纵用轻型柔顺臂》，在Proc。IEEE/RSJ Int. Conf. Intell。机器人系统。，2015年，第1627–1632页。

[126] A. Y. Mersha、S. Stramigioli和R. Carloni, “关于空中机器人的双边远程操作”，IEEE Trans。机器人2014年2月，第30卷第1期，第258–274页。

[127] M. Tognon, B. Yüksel, G. Buondonno, and A. Franchi, "Dynamic decentralized control for protocentric aerial manipulators," in *Proc. IEEE Int. Conf. Robot. Automat.*, Singapore, 2017, pp. 6375–6380.

[128] S. Kim, H. Seo, J. Shin, and H. J. Kim, "Cooperative aerial manipulation using multirotors with multi-DoF robotic arms," *IEEE/ASME Trans. Mechatronics*, vol. 23, no. 2, pp. 702–713, Apr. 2018.

[129] D. Melinger, M. Shomin, and V. Kumar, "Cooperative grasping and transport using multiple quadrotors," in *Proc. Int. Symp. Distrib. Auton. Robots*, 2010, pp. 545–558.

[130] H. Nguyen, S. Park, J. Park, and D. Lee, "A novel robotic platform for aerial manipulation using quadrotors as rotating thrust generators," *IEEE Trans. Robot.*, vol. 34, no. 2, pp. 353–369, Apr. 2018.

[131] R. Ritz and R. D'Andrea, "Carrying a flexible payload with multiple flying vehicles," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2013, pp. 3465–3471.

[132] H. Yang, M. S. Kim, and D. J. Lee, "Distributed rotor-based vibration suppression for flexible object transport and manipulation," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2020, pp. 1230–1236.

[133] K. Sreenath and V. Kumar, "Dynamics, control and planning for cooperative manipulation of payloads suspended by cables from multiple quadrotor robots," in *Proc. Robotics: Sci. Syst.*, 2013.

[134] M. Gassner, T. Cieslewski, and D. Scaramuzza, "Dynamic collaboration without communication: Vision-based cable-suspended load transport with two quadrotors," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2017, pp. 5196–5202.

[135] A. Tagliabue, M. Kamel, R. Siegwart, and J. Nieto, "Robust collaborative object transportation using multiple MAVs," *Int. J. Robot. Res.*, vol. 38, no. 9, pp. 1020–1044, 2019.

[136] H. Yang and D. J. Lee, "Hierarchical cooperative control framework of multiple quadrotor-manipulator systems," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2015, pp. 4656–4662.

[137] F. Caccavale, G. Giglio, G. Muscio, and F. Pierri, "Cooperative impedance control for multiple UAVs with a robotic arm," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2015, pp. 2366–2371.

[138] H. Lee, H. Kim, and H. J. Kim, "Path planning and control of multiple aerial manipulators for a cooperative transportation," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2015, pp. 2386–2391.

[139] S. Kim, H. Seo, J. Shin, andH. J. Kim, "Cooperative in the air: A learning-based approach for the efficient motion planning of aerial manipulators," *IEEE Robot. Automat. Mag.*, vol. 25, no. 4, pp. 76–85, Dec. 2018.

[140] G. Loianno and V. Kumar, "Cooperative transportation using small quadrotors using monocular vision and inertial sensing," *IEEE Robot. Automat. Lett.*, vol. 3, no. 2, pp. 680–687, Apr. 2018.

[141] H-N. Nguyen, S. Park, and D. J. Lee, "Aerial tool operation system using quadrotors as rotating thrust generators," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2015, pp. 1285–1291.

[142] M. Mohammadi, A. Franchi, D. Barcelli, and D. Prattichizzo, "Cooperative aerial tele-manipulation with haptic feedback," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2016, pp. 5092–5098.

[143] T. W. Nguyen, L. Catoire, and E. Garone, "Control of a quadrotor and a groud vehicle manipulating an object," *Automatica*, vol. 105, pp. 384–390, 2019.

[144] N. Staub, M. Mohammadi, D. Bicego, D. Prattichizzo, and A. Franchi, "Towards robotic MAGMaS: Multiple aerial-ground manipulator systems," in *Proc. IEEE Int. Conf. Robot. Automat.*, Singapore, 2017, pp. 1307–1312.

[145] H. Yang, N. Staub, A. Franchi, and D. J. Lee, "Modeling and control of multiple aerial-ground manipulator system (magmas) with load flexibility," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2018, pp. 1–8.

[146] B. Gabrich, D. Saldana, V. Kumar, and M. Yim, "A flying gripper based on cuboid modular robots," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2018, pp. 7024–7030.

[147] R. Oung, F. Bourgault, M. Donovan, and R. D'Andrea, "The distributed flight array," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2010, pp. 601–607.

[148] M. Zhao, T. Anzai, F. Shi, X. Chen, K. Okada, and M. Inaba, "Design, modeling, and control of an aerial robot dragon: A dual-rotor-embedded multilink robot with the ability of multi-degree-of-freedom aerial transformation," *IEEE Robot. Automat. Lett.*, vol. 3, no. 2, pp. 1176–1183, Apr. 2018.

[149] S. Park, Y. Lee, J. Heo, and D. Lee, "Pose and posture estimation of aerial skeleton systems for outdoor flying," in *Proc. Int. Conf. Robot. Automat.*, 2019, pp. 704–710.

[150] F. Shi, M. Zhao, M. Murooka, K. Okada, and M. Inaba, "Aerial regrasping: Pivoting with transformable multilink aerial robot," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2020, pp. 200–207.

[151] M. Zhao *et al.*, "Transformable multirotor with two-dimensional multilinks: Modeling, control, and whole-body aerial manipulation," *Int. J. Robot. Res.*, vol. 37, no. 9, pp. 1085–1112, 2018.

[152] T. Anzai *et al.*, "Multilinked multirotor with internal communication system for multiple objects transportation based on form optimization method," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2017, pp. 5977–5984.

[153] C. Masone, M. Mohammadi, P. R. Giordano, and A. Franchi, "Shared planning and control for mobile robots with integral haptic feedback," *Int. J. Robot. Res.*, vol. 37, no. 11, pp. 1395–1420, 2018.

[154] G. Gioioso, M. Mohammadi, A. Franchi, and D. Prattichizzo, "A force-based bilateral teleoperation framework for aerial robots in contact with the environment," in *Proc. IEEE Int. Conf. Robot. Automat.*, Seattle, WA, May 2015, pp. 318–324.

[155] J. Lee *et al.*, "Visual-inertial telepresence for aerial manipulation," 2020, *arXiv:2003.11509*.

[156] G. Gioioso, A. Franchi, G. Salvietti, S. Scheggi, and D. Prattichizzo, "The flying hand: A formation of UAVs for cooperative aerial tele-manipulation," in *Proc. IEEE Int. Conf. Robot. Automat.*, Hong Kong, May 2014, pp. 4335–4341.

[157] M. De Stefano, R. Balachandran, J. Artigas, and C. Secchi, "Reproducing physical dynamics with hardware-in-the-loop simulators: A passive and explicit discrete integrator," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2017, pp. 5899–5906.

[158] G. A. Yashin, D. Trinitatova, R. T. Agishev, R. Ibrahimov, and D. Tsetserukou, "AeroVR: Virtual reality-based teleoperation with tactile feedback for aerial manipulation," in *Proc. 19th Int. Conf. Adv. Robot.*, 2019, pp. 767–772.

[159] Y. Wu, J. Song, J. Sun, F. Zhu, and H. Chen, "Aerial grasping based on VR perception and haptic control," in *Proc. IEEE Int. Conf. Real-time Comput. Robot.*, 2018, pp. 556–562.

[160] A. Santamaria-Navarro, G. Loianno, J. Solà, V. Kumar, and J. A. Cetto, "Autonomous navigation of micro aerial vehicles using high-rate and low-cost sensors," *Auton. Robots*, vol. 42, no. 6, pp. 1263–1280, 2017.

[161] W. Martens, Y. Poffet, P. R. Soria, R. Fitch, and S. Sukkarieh, "Geometric priors for Gaussian process implicit surfaces," *IEEE Robot. Automat. Lett.*, vol. 2, no. 2, pp. 373–380, Apr. 2017.

[162] C. Kanellakis and G. Nikolakopoulos, "Guidance for autonomous aerial manipulator using stereo vision," *J. Intell. Robotic Syst.*, vol. 8, pp. 1–13, 2019.

[163] S. Kim, H. Seo, S. Choi, and H. J. Kim, "Vision-guided aerial manipulation using a multirotor with a robotic arm," *IEEE/ASME Trans. Mechatronics*, vol. 21, no. 4, pp. 1912–1923, Aug. 2016.

[164] L. de Silva, M. Gharbi, A. K. Pandey, and R. Alami, "A new approach to combined symbolic-geometric backtracking in the context of human-robot interaction," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2014, pp. 3757–3763.

[165] H. Lv and C. Lu, "An assembly sequence planning approach with a discrete particle swarm optimization algorithm," *Int. J. Adv. Manuf. Technol.*, vol. 50, no. 5, pp. 761–770, Sep. 2010.

[166] G. Tian, M. Zhou, and J. Chu, "A. chance constrained programming approach to determine the optimal disassembly sequence," *IEEE Trans. Automat. Sci. Eng.*, vol. 10, no. 4, pp. 1004–1013, Oct. 2013.

[167] A. Boeuf, J. Cortés, R. Alami, and T. Siméon, "Enhancing sampling-based kinodynamic motion planning for quadrotors," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2015, pp. 2447–2452.

[168] M. Tognon, E. Cataldi, H. A. T. Chavez, G. Antonelli, J. Cortés, and A. Franchi, "Control-aware motion planning for task-constrained aerial manipulation," *IEEE Robot. Automat. Lett.*, vol. 3, no. 3, pp. 2478–2484, Jul. 2018.

[169] A. Caballero, M. Bejar, A. Rodriguez-Castaño, and A. Ollero, "Motion planning with dynamics awareness for long reach manipulation in aerial robotic systems with two arms," *Int. J. Adv. Robotic Syst.*, vol. 15, no. 3, 2018, Art. no. 1729881418770525.

[170] J. Thomas, J. Polin, K. Sreenath, and V. Kumar, "Avian-inspired grasping for quadrotor micro UAVs," in *Proc. ASME Int. Des. Eng. Tech. Conf. Comput. Inf. Eng. Conf.*, 2013.

[171] P. Hannibal, O. Koji, L. Robert, and S. Kazuhiro, "A multirotor platform employing a three-axis vertical articulated robotic arm for aerial manipulation tasks," in *Proc. IEEE/ASME Int. Conf. Adv. Intell. Mechatronics*, 2018, pp. 478–485.

[127] M. Tognon、B. Yüksel、G. Buondonno和A. Franchi, "原心式空中机械手的动态分散控制"，在Proc。IEEE内部配置机器人。自动装置。，新加坡，2017年，第6375–6380页。

[128] S. Kim, H. Seo, J. Shin和H. J. Kim, "使用多旋翼和多自由度机械臂的协同空中操纵"，IEEE/ASME Trans。《机电一体化》，第23卷，第2期，第702–713页，2018年4月。

[129] D. Melinger、M. Shomin和V. Kumar, "使用多个四转子的协同抓取和运输"，在Proc。国际研讨会。发行版。奥顿。机器人，2010年，第545–558页。

[130] H. Nguyen、S. Park、J. Park和D. Lee, "一种利用四旋翼作为旋转推力发生器进行空中操纵的新型机器人平台"，IEEE Trans。机器人第34卷第2期，第353–369页，2018年4月。

[131] R. Ritz和R.D'Andrea在Proc中"携带多个飞行器的灵活有效载荷"。IEEE/RSJ Int. Conf. Intell。机器人系统。，2013年，第3465–3471页。

[132] H. Yang, M. S. Kim和D. J. Lee, "柔性物体运输和操纵的基于转子的分布式振动抑制"，在Proc。IEEE内部配置机器人。自动装置。，2020年，第1230–1236页。

[133] K. Sreenath和V. Kumar, "多个四旋翼机器人电缆悬挂的有效载荷协同操纵的动力学、控制和规划"，在Proc。机器人学：Sci。系统。，2013

[134] M. Gassner、T. Cieslewski和D. Scaramuzza, "无通信的动态协作：基于视觉的带两个四转子的电缆悬浮负载运输"，在Proc。IEEE内部配置机器人。自动装置。，2017年，第5196–5202页。

[135] A. Tagliabue, M. Kamel, R. Siegwart和J. Nieto, "使用多个MAV的鲁棒协作对象运输"，Int. J. Robot。Res.,第38卷，第9期，第1020-10442019页。

[136] H. Yang和D. J. Lee, "多个四转子机械手系统的分层协同控制框架"，在Proc。IEEE内部配置机器人。自动装置。，2015年，第4656–4662页。

[137] F.Caccavare、G. Giglio、G. Muscio和F. Pierri, "带机械臂的多无人机的协同阻抗控制"，在Proc。IEEE/RSJ Int. Conf. Intell。机器人系统。，2015年，第2366–2371页。

[138] H. Lee、H. Kim和H. J. Kim, "用于合作运输的多个空中机械手的路径规划和控制"，在Proc。IEEE/RSJ Int. Conf. Intell。机器人系统。，2015年，第2386–2391页。

[139] S. Kim、H. Seo、J. Shin和H。J. Kim, "空中合作：空中机械手有效运动规划的基于学习的方法"，IEEE Robot。自动装置。杂志，第25卷，第4期，第76–85页，2018年12月。

[140] G. Loianno和V. Kumar, "使用单目视觉和惯性传感的小型四旋翼协同运输"，IEEE Robot。自动装置。莱特。，2018年4月，第3卷第2期，第680–687页。

[141] H-N. Nguyen, S. Park和D. J. Lee, "使用四转子作为旋转推力发生器的航空工具操作系统"，在Proc。IEEE/RSJ Int. Conf. Intell。机器人系统。，2015年，第1285–1291页。

[142] M. Mohammadi、A. Franchi、D. Barcelli和D. Prattichizzo, "具有触觉反馈的交互式空中遥控操作"，在Proc。IEEE/RSJ Int. Conf. Intell。机器人系统。，2016年，第5092–5098页。

[143] T. W. Nguyen, L. Catoire和E. Garone, "四旋翼和地面车辆操纵物体的控制"，Automatica,第105卷，384-3902019页。

[144] N. Staub、M. Mohammadi、D. Bicego、D. Prattichizzo和A. Franchi, "走向机械岩浆：多空中地面机械手系统"，在Proc。IEEE内部配置机器人。自动装置。，新加坡，2017年，第1307–1312页。

[145] H. Yang, N. Staub, A. Franchi和D. J. Lee, "具有负载灵活性的多空中地面机械手系统（magmas）的建模和控制"，在Proc。IEEE/RSJ Int. Conf. Intell。机器人系统。，2018年，第1–8页。

[146] B. Gabrich、D. Saldana、V. Kumar和M. Yim, "基于长方体模块化机器人的飞行夹持器"，在Proc。IEEE内部配置机器人。自动装置。，2018年，第7024–7030页。

[147] R·翁、F·布尔高尔特、M·多诺万和R·D·安德里亚，《分布式飞行阵列》，在Proc。IEEE内部配置机器人。自动装置。，2010年，第601–607页。

[148] M. Zhao, T. Anzai, F. Shi, X. Chen, K. Okada和M. Inaba, "空中机器人龙的设计、建模和控制：具有多自由度空中转换能力的双转子嵌入式多链路机器人"，IEEE Robot。自动装置。莱特。，第3卷第2期，第1176–1183页，2018年4月。

[149] S. Park, Y. Lee, J. Heo和D. Lee, "户外飞行用空中骨架系统的姿势和姿势估计"，在Proc。内部形态机器人。自动装置。，2019年，第704–710页。

[150] 施福荣、赵明明、木鲁卡、冈田康和稻叶，"空中加油：可变形多线空中机器人的旋转"，在Proc。IEEE内部配置机器人。自动装置。，2020年，第200–207页。

[151] M. Zhao等人，"具有二维多关节的可变换多转子：建模、控制和全身空中操纵"，Int. J. Robot。Res.,第37卷，第9期，第1085–1112页，2018年。

[152] T. Anzai等人，"基于形状优化方法的多目标运输用带内部通信系统的多连接多转子"，在Proc。IEEE/RSJ Int. Conf. Intell。机器人系统。，2017年，第5977–5984页。

[153] C. Masone、M. Mohammadi、P. R. Giordano和A. Franchi, "具有整体触觉反馈的移动机器人共享规划和控制"，Int. J. Robot。Res.,第37卷，第11期，第1395–1420页，2018年。

[154] G.Giioso、M. Mohammadi、A. Franchi和D. Prattichizzo, "A.与环境接触的空中机器人基于力量的双边远程操作框架"，在Proc。IEEE内部配置机器人。自动装置。，华盛顿州西雅图，2015年5月，第318–324页。

[155] J. Lee等人，"空中操纵的视觉惯性临场感"，2020年，*arXiv:2003.11509*.

[156] G. Gioioso、A. Franchi、G. Salvietti、S. Scheggi和D. Prattichizzo, 《飞之手：用于协同空中遥控的无人机编队》，在Proc。IEEE内部配置机器人。自动装置。，香港，2014年5月，第4335–4341页。

[157] M. De Stefano、R. Balachandran、J. Artigas和C. Secchi, "用硬件在环模拟器再现物理动力学：一个被动的显式离散积分器"，在Proc。IEEE内部配置机器人。Au- tomat。，2017年，第5899–5906页。

[158] G.A.Yashin,D.Trinitova，R. T. Agishev, R. Ibrahimov和D.Tsetsurukou，"AeroVR：基于虚拟现实的远程操作，用于空中操作的触觉反馈"，在Proc。第19国际形态高级机器人。，2019年，第767–772页。

[159] Y、 Wu, J. Song, J. Sun, F. Zhu和H. Chen, "基于VR感知和触觉控制的空中抓取"，摘自Proc。IEEE内部配置实时计算机。机器人2018年，第556–562页。

[160] A. Santamaria Navarro、G. Loianno、J.Solá、V. Kumar和J. A. Cetto, "使用高速率和低成本传感器的微型飞行器自动导航"，Auton。《机器人》，第42卷，第6期，第1263–1280页，2017年。

[161] W. Martens, Y. Poffet, P. R. Soria, R. Fitch和S. Sukkarieh, "高斯过程隐式曲面的几何先验"，IEEE Robot。自动装置。莱特。，2017年4月，第2卷，第373–380页。

[162] C. Kanellakis和G. Nikolakopoulos, "使用立体视觉的自动空中机械手指南"，J. Intell。机器人系统。，2019年第8卷第1–13页。

[163] S. Kim、H. Seo、S. Choi和H. J. Kim, "使用带机械臂的多转子进行视觉引导的空中操纵"，IEEE/ASME Trans。《机电一体化》，第21卷，第4期，1912–1923页，2016年8月。

[164] L. de Silva、M. Gharbi、A. K. Pandey和R. Alami, "在人-机器人交互环境中组合符号几何回溯的新方法"，在Proc。IEEE内部配置机器人。自动装置。，2014年，第3757–3763页。

[165] H. Lv和C. Lu, "采用离散粒子群优化算法的装配序列规划方法"，Int. J. Adv. Manuf. Technol。，第50卷第5期，第761–770页，2010年9月。

[166] G. Tian, M. Zhou和J. Chu, "A.确定最佳拆卸顺序的机会约束规划方法"，IEEE Trans。自动装置。Sci。《工程》第10卷第4期，第1004–1013页，2013年10月。

[167] A. Boeuf、J. Cortés、R. Alami和T. Siméon, "增强基于采样的四旋翼动力学运动规划"，在Proc。IEEE/RSJ Int. Conf. Intell。机器人系统。，2015年，第2447–2452页。

[168] M.托格农、E.卡特迪、H. A. T.查韦斯、G.安东内利、J.科尔特斯和A. Franchi, "任务约束空中操纵的控制感知运动规划"，IEEE Robot。自动装置。莱特。，第3卷第3期，第2478–2484页，2018年7月。

[169] A. Caballero、M. Bejar、A. Rodriguez Castaño和A. Ollero, "双臂空中机器人系统中长距离操纵的动力学感知运动规划"，国际期刊《机器人系统》。，2018年第15卷第3期，第。编号：172988418770525。

[170] J. Thomas、J. Polin、K. Sreenath和V. Kumar, "四旋翼微型无人机的鸟类抓取"，在Proc。美国机械工程师协会。工程技术形态计算机。Inf.工程配置，2013年。

[171] P. Hannibal、O. Koji、L. Robert和S. Kazuhiro, "一种多旋翼平台，采用三轴垂直铰接机械臂进行空中操纵任务"，在Proc。IEEE/ASME国际会议高级会议。机电一体化，2018年，第478–485页。

[172] H. W. Wopereis, T. D. van der Molen, T. H. Post, S. Stramigioli, and M. Fumagalli, "Mechanism for perching on smooth surfaces using aerial impacts," in *Proc. IEEE Int. Symp. Safety, Security, Rescue Robot.*, 2016, pp. 154–159.

[173] A. López-Lora, P. J. Sánchez-Cuevas, A. Garofano, A. Suárez, A. Ollero, and G. Heredia, "MHYRO: Modular hybrid robot for contact inspection and maintenance in oil and gas plants," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2020, pp. 1268–1275.

[174] A. S. Saeed, A. B. Younes, C. Cai, and G. Cai, "A survey of hybrid unmanned aerial vehicles," *Prog. Aerosp. Sci.*, vol. 98, pp. 91–105, 2018.

[175] C. Papachristos, K. Alexis, and A. Tzes, "Design and experimental attitude control of an unmanned tilt-rotor aerial vehicle," in *Proc. Int. Conf. Adv. Robot.*, 2011, pp. 465–470.

[176] S. Verling, T. Stastny, G. Bättig, K. Alexis, and R. Siegwart, "Model-based transition optimization for a VTOL tailsitter," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2017, pp. 3939–3944.

[177] S. Mintchev and D. Floreano, "Adaptive morphology: A design principle for multimodal and multifunctional robots," *IEEE Robot. Automat. Mag.*, vol. 23, no. 3, pp. 42–54, Sep. 2016.

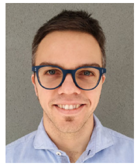
[178] S. A. Ansari, R. Żbikowski, and K. Knowles, "Aerodynamic modelling of insect-like flapping flight for micro air vehicles," *Prog. Aerosp. Sci.*, vol. 42, no. 2, pp. 129–172, 2006.

[179] M. I. Woods, J. F. Henderson, and G. D. Lock, "Energy requirements for the flight of micro air vehicles," *Aeronaut. J.*, vol. 105, no. 1045, pp. 135–149, 2001.

[180] G. Sachs, "New model of flap-gliding flight," *J. Theor. Biol.*, vol. 377, pp. 110–116, 2015.

[181] M. Tognon, R. Alami, and B. Siciliano, "Physical human-robot interaction with a tethered aerial vehicle: Application to a force-based human guiding problem," *IEEE Trans. Robot.*, early access, Feb. 11, 2021, doi: 10.1109/TRO.2020.3038700.

[182] A. Tagliabue, A. Paris, S. Kim, R. Kubicek, S. Bergbreiter, and J. P. How, "Touch the wind: Simultaneous airflow, drag and interaction sensing on a multirotor," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2020, pp. 1645–1652.



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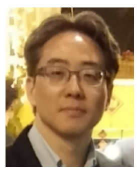

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[172] H. W.沃佩雷斯、T. D.范德莫伦、T. H.波斯特、S.斯特拉米吉奥利和
M. Fumagalli, "利用空中撞击在光滑表面上栖息的机制"，在Proc。IEEE国际研讨会。安全，保安，救援机器人。，2016年，第154–159页。

[173] A. López Lora、P. J. Sánchez Cuevas、A.Garofao、A. Suárez、A. Ollero和G. Heredia, "MHYRO：用于油气厂接触检查和维护的模块化混合机器人"，摘自Proc。IEEE/RSJ Int. Conf. Intell。机器人系统。，2020年，第1268–1275页。

[174] A. S.赛义德、A. B.尤恩斯、C.蔡和G.蔡，"混合式无人机概览"，Prog。Aerosp。Sci。，2018年第98卷第91–105页。

[175] C. Papachristos, K. Alexis和A. Tzes, "无人倾转旋翼飞行器的设计和实验姿态控制"，在Proc。内部形态高级机器人。，2011年，第465–470页。

[176] S. Verling、T. Stastny、G. Bättig、K. Alexis和R.Siegwart,"VTOL尾座的基于模型的过渡优化"，在Proc。IEEE内部配置机器人。自动装置。，2017年，第3939–3944页。

[177] S. Mintchev和D. Floreano, "自适应形态学：多模态和多功能机器人的设计原则"，IEEE Robot。自动装置。杂志，第23卷，第3期，第42–54页，2016年9月。

[178] S、A. Ansari、R. Zˇ bikowski和K. Knowles, "微型飞行器类昆虫扑翼飞行的空气动力学建模"，Prog。Aerosp。Sci。，第42卷，第2期，第129–172页，2006年。

[179] M. I.伍兹、J. F.亨德森和G. D.洛克，"微型飞行器飞行的能量需求"，Aeronaut。《华尔街日报》，第105卷，第1045号，第135–149页，2001年。

[180] G. Sachs, "襟翼滑翔飞行的新模型"，J. Theor。Biol。，第377卷，第110–116页，2015年。

[181] M. Tognon、R. Alami和B. Siciliano, "人-机器人与系留飞行器的物理交互：基于力的人类引导问题的应用"，IEEE Trans。机器人 2021 2月11日，内政部，提前访问: 10.1109/TRO.2020.3038700.

[182] A. Tagliabue、A. Paris、S. Kim、R. Kubicek、S. Bergbreiter和J. P. How, "触风：多转子上的同步气流、阻力和相互作用感应"，在Proc。IEEE/RSJ Int. Conf. Intell。机器人系统。，2020年，第1645–1652页。

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