Robotics and Autonomous Systems 107 (2018) 221–235

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

journal homepage: www.elsevier.com/locate/robot

Aerial manipulation—A literature survey

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HIGHLIGHTS

- Comprehensive survey on unmanned aerial manipulator applications.
- Overview of UAV platforms and manipulation/interaction mechanisms.
- Overview of missions and operational scenarios.
- Overview of the design, modeling, estimation/control of unmanned aerial manipulators.
- Identification of current shortcoming and gaps and suggesting future directions.

ARTICLE INFO

Article history:
Received 10 August 2017
Received in revised form 14 May 2018
Accepted 24 June 2018
Available online 30 June 2018

Keywords:
Aerial manipulation
UAV
Quadcopter
Manipulator
Modeling
Control

ABSTRACT

This paper presents a literature survey on aerial manipulation. First of all, an extensive study of aerial vehicles and manipulation/interaction mechanisms in aerial manipulation is presented. Various combinations of aerial vehicles and manipulators and their applications in different missions are discussed. Next, two main modeling methods and a detailed investigation of existing estimation and control techniques in aerial manipulation are explained. Finally the shortcomings of current aerial manipulation research are highlighted and a number of directions for future research are suggested.

1. Introduction

In recent years, a significant growth in Unmanned Aerial Vehicle (UAV) industry has been realized. As an example, in the United States only, there were approximately a million UAV or "drone" gifts for Christmas 2015 [1]. To this date, UAVs have been used in applications such as remote sensing of agricultural products [2], forest fire monitoring [3], search and rescue [4], border monitoring [5], transmission line inspection [6], and plant assets inspection [7]. Fully functional UAVs for plant inspection have appeared as recently as 2010 for UK onshore oil refineries [8]. In 2012, the supermajor oil and gas company, British Petroleum, established research teams to develop the necessary technologies to use UAVs for oil pipeline inspection in Prudhoe, Alaska [9] and over the course of only a few years, the technology has matured to become the standard practice for onshore and offshore platforms [7]. The above achievements have benefited various industries tremendously; however, an important common shortcoming in the mentioned applications is that the UAV is employed to merely sense, monitor and "see" the environment, but physical interaction with the environment is strictly avoided. Motivated by this, researchers in the last few years have begun examining applications in which a UAV is required to perform perching, grasping, and manipulation [10–15]. This new area of research, usually known as aerial manipulation, encourages physical interaction of the UAV with its surrounding environment and enables UAVs to perform a whole new set of missions.

Aerial manipulation falls within a well-studied broad research category known as mobile manipulation. However, most of the research carried out in mobile manipulation focuses on ground robots. The main distinct challenges in the aerial manipulation problem are:

1. Unlike ground robots, UAVs do not have a stable base and therefore forces and torques generated by the presence and movement of the manipulation mechanism and/or the payload directly affect the vehicle's position, attitude and even its stability;

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https://doi.org/10.1016/j.robot.2018.06.012
0921-8890/

Fig. 1. Valve turning operation by a UAM [26].

2. Unlike ground robots, the performance of UAVs' propulsion system vary in close vicinity of the ground and/or walls;
3. UAVs are often underactuated platforms with highly non-linear coupled dynamics, introducing further complications into their control design; and
4. UAVs usually have stringent payload weight constraints and therefore cannot accommodate industrial dexterous robotic manipulators.

The above challenges encourage the development of a new research theme for the aerial manipulation problem.

An aerial manipulation system, viz. Unmanned Aerial Manipulator (UAM) hereafter, consists of two subsystems, namely a UAV and an interaction/manipulation mechanism (such as a robotic manipulator or a rigid tool) employed to physically interact with the environment. A rich amount of research literature and a number of review papers have been published on either of the above subsystems. As an example, in [16], a comprehensive survey of control algorithms for UAVs was presented. In that work, a number of schemes such as Proportional–Derivative–Integral (PID), Linear Quadratic Regulator (LQR), H∞, sliding mode variable structure, backstepping, and adaptive control along with their advantages and drawbacks in the control of UAVs with Vertical Take-Off and Landing (VTOL) capabilities, e.g. the quadcopter, were discussed. A detailed review of motion planning and trajectory planning algorithms for UAV guidance was also presented in [17]. Later, a review of path planning algorithms in the presence of disturbances and uncertainty was given in [18]. Also, a comprehensive literature survey on manipulation and grasping in robotic manipulation was given in [19]. While the above works summarize a broad body of literature on UAVs and robotic manipulators, they do not specifically discuss UAMs. In fact, to the best of authors' knowledge, there is no published review paper on aerial manipulation including mission scenarios, mathematical modeling, and control schemes used in UAMs.

Aerial manipulation is a new field of research. Some of the pioneering works in this area appeared in the first years of the current decade [10,11,20–22] where the manipulation usually consisted of a gripper rigidly attached to a UAV body or was based on tethered configurations. Over the course of a few years, aerial manipulation has considerably evolved and more recent works, e.g. [14,15,23–26], address challenging problems such as valve turning (see Fig. 1) and pick-and-place by several Degrees-of- Freedom (DoF) robotic manipulators. The authors believe that the coming years will bring further advancement in aerial manipulation and will enable more practical and reliable UAMs in a variety of applications.

The rest of this paper is organized as follows. Section 2 describes the most commonly used UAVs and manipulation/interaction mechanisms in aerial manipulation systems. Section 3 thoroughly studies missions and scenarios realized, to this date, in the area of aerial manipulation. Two main modeling methodologies and various control schemes in aerial manipulation are presented in Sections 4 and 5, respectively. Conclusions and directions for future research are presented in Section 6.

2. The physical subsystems of UAMs

In general, an aerial manipulation system contains two main physical subsystems, a UAV platform and a manipulation mechanism, with the necessary sensors and control systems for its autonomous or semi-autonomous functionality. In this section, we describe the most common subsystems of a UAM as well as the possible sensory configurations considered for various applications.

2.1. The UAV platform

Historically, helicopters were the primary platforms for manned aerial manipulation applications as early as 1950s and 1960s [27–32]. These manned missions covered a broad spectrum ranging from load transportation and power-line inspection/maintenance to seed dispersal (to name a few). With the advancement in autonomous systems, unmanned helicopters were able to visually detect and magnetically pick up and transport objects in outdoor environment as early as in 1990s [33]. Successful autonomous take-off and landing were also reported by several research groups in the same time period [34–36]. Shortly afterwards, autonomous aerial refueling missions were also successfully achieved [37–39]. Review of the available literature shows that fixed-wing UAVs have not been employed in aerial manipulation problems, except for aerial refueling, as they require to maintain a minimum forward velocity (stall velocity) and therefore are not discussed in this work. On the contrary, rotary-wing UAVs have been and remain the main platforms for aerial manipulation applications. A number of rotary-wing vehicles have been used in UAMs and are discussed in the following paragraphs. Also, airships, a class of Lighter-Than-Air (LTA) vehicles, can be used as the UAV in aerial manipulation applications. As an example, in [40,41], the authors proposed a hybrid UAV (quadcopter + airship) equipped with 3 identical robotic arms to perform grasping tasks. However, airship systems are not frequently employed today mainly due to their low payload-to- volume ratio, high air resistance and sensitivity to aerodynamic disturbances as well as the lack of proper infrastructure required for their operation.

Among rotary-wing UAVs with hovering capability, octoquads [42], hexquads [43,44], quadcopters [45–51], tri- rotors [52], conventional helicopters [20,53–56], and ducted-fan vehicles [57–59] have been used in UAM systems. From the available literature, it can be concluded that quadcopters are by far the most widely-used UAV platforms for aerial manipulation, followed by small-size helicopters. This is mainly due to the simplicity of quadcopter mechanical design and hovering capability, complemented by the low-cost, agility and existing precise control schemes for these flying vehicles [60]. The characteristics of some UAV platforms used in aerial manipulation are presented in Table 1 where the very limited payload weight budget of most of these platforms is clearly seen. In fact, except for the octoquad AMUSE [42] depicted in Fig. 2, most multi- rotor UAVs used for research weigh less than 2 kg with a payload of a few hundreds of grams [61]. This constitutes a real problem in the design of UAMs since most manipulation mechanisms to be attached to the UAV system impose a total allowable payload exceeding the capabilities of the majority of the available UAVs (as given in Table 1). For instance, it was reported in [55,62] that a total UAV payload of approximately 10 kg is generally required in most practical applications involving UAMs equipped with fully actuated robotic arms (see Section 2.2). Fig. 3 shows a 6.5 kg MK1 robotic arm that can be exploited in UAMs