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Design of a lightweight dual arm system for aerial manipulation☆

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ABSTRACT

This paper presents the development and experimental validation of a low weight and inertia, human-size and highly dexterous dual arm system designed for aerial manipulation with multirotor platform. The arms, weighting 1.8 kg in total and with a maximum lift load per arm around 0.75 kg, provide five degrees of freedom (DOF) for end-effector positioning and wrist orientation. A customized aluminum frame structure supports the servo actuators, placing most part of the mass close to the shoulder structure in order to reduce the inertia. A double flange bearing mechanism in side-by-side configuration isolates the servos from impacts and radial/axial overloads, increasing robustness. This is important to prevent that the arms are damaged during physical interactions with the environment, as they should support the kinetic energy of the whole platform. The motivation in the development of a dual arm aerial manipulator is extending the range of applications and tasks that can be performed with respect to the single arm case, like grasping large objects or assembling. The paper covers the kinematic and dynamic modeling of the aerial robot, proposing a control scheme that deals with the technological limitations of the smart servo actuators. The performance of the arms and the interactions with the aerial platform are evaluated in test bench experiments. The proposed dual arm design is validated through outdoor flight tests with two commercial hexarotor platforms equipped with standard industrial autopilots.

1. Introduction

1.1. State of the art in aerial manipulation

The aerial manipulation field extends the range of applications of vertical take-off and landing (VTOL) unmanned aerial vehicles (UAVs), either autonomous helicopters or multi-rotors [1,2,3]. Including one or more robotic arms in an aerial platform allows the execution of different inspection and maintenance tasks in industrial scenarios of difficult access for human operators in both indoors [4] and outdoors [5], reducing the time and cost associated to the deployment of persons, vehicles, cranes and tools typically employed. Some examples include inspection and maintenance of high altitude pipes in chemical plants [6], structure constructions [7], installation and retrieval of sensor devices in polluted areas, repair of cracks in the blades of wind turbines, or replacing the batteries of remote robots. The effort now is focused in the development of low weight grippers and robotic arms to be integrated in these vehicles. Several mechanisms have been proposed. Quadrotor grasping and perching using impactive and ingressive grippers is presented in [8]. A simple 2-DOF robotic arm, 0.37 kg weight and 0.32 m length, is shown in [9]. Valve turning on flight with a quadrotor is demonstrated in [10] with two 2-DOF arms, generating a torque in the yaw angle with the propellers while grasping the valve. A large hexarotor platform equipped with two teleoperated arms has been presented for object transportation [11]. The 5 DOF lightweight robotic arm presented in [12] reduces the inertia of the manipulator employing timing belts for transmitting the motion from the actuators placed at the base to the joints. The single DOF arm with flexible joint developed in [13] employs a Dynamixel servo as actuator and a pair of extension springs as transmission mechanism between the servo pulley and the link pulley.

In our previous work, we developed two prototypes of lightweight and compliant arms for aerial manipulation. Reference [14] is a particular implementation of the Series Elastic Actuators [15], consisting of a linear actuator and a pair of extension springs acting as elastic tendons on the elbow joint, used for estimating the payload at the wrist point but also for detecting collisions on the forearm. Mechanical joint compliance with deflection measurement allows the estimation and control of the contact forces in a 3-DOF arm [16]. Table 1 compares the proposed design w.r.t. other prototypes intended to aerial manipulation. Note that this manipulator provides the highest number of DOF's and maximum lift load and reach.

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Table 1
Comparison of different prototypes of lightweight robotic arms for aerial manipulation.

Reference	Single/dual arm	Stiff/compliant	Total DOF's	Weight/max. lift load[a] (kg)	Reach (m)	Max. stall torque (N m)	Actuators
Proposed	Dual	Stiff	10	1.8/0.75[a]	0.5	7.5	Herkulex
[10]	Dual	Stiff	4	NA/NA	NA	3.1	Dynamixel
[11]	Dual	Stiff	NA	NA/NA	NA	NA	NA
[9]	Single	Stiff	2	0.37/NA	0.32	3.1	Dynamixel
[43]	Single	Stiff	6	1.4/NA	0.45	10.0	Dynamixel
[11]	Single	Stiff	5	0.25/0.2	0.3	1.2	DC motor
[13]	Single	Compliant	1	0.36/NA	0.18	1.5	Dynamixel
[16]	Single	Compliant	3	0.3/0.2[a]	0.5	1.17	Herkulex
[17]	Dual	Compliant	8	1.3/0.2[a]	0.5	2.34	Herkulex

[a] Maximum lift load per arm in the worst case (0–90° rotation in the shoulder pitch joint).

Bimanual manipulation with multi-rotors has been addressed only in a few recent works [10,11,17]. However, dual arm manipulators have been already considered in space applications for several years [26]. In this sense, the redundancy provided by a second arm in a free-floating space robot can be exploited for optimizing the torque control of the whole manipulator [27], planning the trajectories of the arms in such a way that robot base is stabilized [28]. Several control methods have been developed and tested in dual arm systems with fixed or mobile base. Reference [29] deals with the cooperative control of two 3-DOF flexible link manipulators when holding an object in a closed kinematic chain. Dexterous manipulation with DLR humanoid robot Justin is shown in [30]. Impedance control is evaluated in [31] with two 6-DOF industrial manipulators. Cartesian impedance control is also applied for the real-time motion tracking in an anthropomorphic dual arm [32]. An extensive survey on other dual arm systems can be found in [33].

One of the main problems in the control of an aerial manipulation robot is the influence of arms motion over UAV attitude due to the dynamic coupling between both parts. Different control schemes have been proposed and experimentally validated with multi-rotor platforms, including PI-D [18], variable parameter integral backstepping [2], adaptive controllers [19], and other multi-layer architectures [20,21]. When the aerial platform is intended to perform grasping and transportation operations, it results convenient to have a method for estimating the weight of the grasped object, and hence its influence on the UAV dynamic behavior [22,23]. Helicopter stability is analyzed in [24] when contact forces are introduced in the aircraft through a compliant end-effector attached to the base employed for object grasping. The stability of a PID controller for flight control during object grasping and release operations is demonstrated in simulation and experimentally. Reference [25] presents a control architecture for compliant interaction between a quadrotor equipped with an n-DOF manipulator and the environment.

1.2. Contribution of this work

This paper describes a dual arm aerial manipulator for outdoor operation consisting of a human size dual arm integrated in a commercial hexarotor. Whereas most aerial manipulators that can be found in the literature are research prototypes evaluated in indoor testbeds, the proposed dual arm design extends the range of tasks that can be accomplished with respect to the single arm case, satisfying four requirements essential in the successful application of the aerial manipulation technology outdoors: (1) high payload (up to 0.75 kg per arm) for manipulating a wide variety of objects and tools, (2) high joint/Cartesian speed (300 °/s, 2.5 m/s at end effector) for agile task execution, (3) positioning accuracy and reliability for object grasping, and (4) mechanical robustness for extending the lifespan of the actuators. The manipulator is built with smart servo actuators and a customized anodized aluminum frame structure that reduces the manufacturing cost. The accuracy, repeatability and smoothness in the operation of the arms are evaluated in test bench experiments. The paper also addresses their integration in a hexarotor platform, including the identification of motion constraints and the electronics. The kinematics and dynamics of the dual arm aerial manipulator are derived, proposing a control scheme that makes use of the manipulator dynamics for compensating the reaction wrenches. The interactions between the manipulator and the aerial platform are experimentally identified in testbench in hovering conditions. Finally, the dual arm design is validated through an extensive set of outdoor flight tests with two commercial hexarotor platforms equipped with standard industrial autopilots (Fig. 1), showing that the influence of high speed motions of the arms over the aerial vehicle is low. The video of the flight tests is provided as attachment, or it can be seen in [44].

The rest of the paper is organized as follows. Section 2 begins detailing the motivations for considering a dual arm robot in aerial manipulation applications. The design requirements are then presented and followed by the description of the developed dual arm. Section 3 describes the aerial manipulator, including its specifications, the electronics, and the motion constraints for the arms. Section 4 describes the kinematics and dynamics of the dual arm system, proposing a control scheme for the aerial manipulator in Section 5. Experimental results are presented in Section 6, summarizing the conclusions in Section 7.

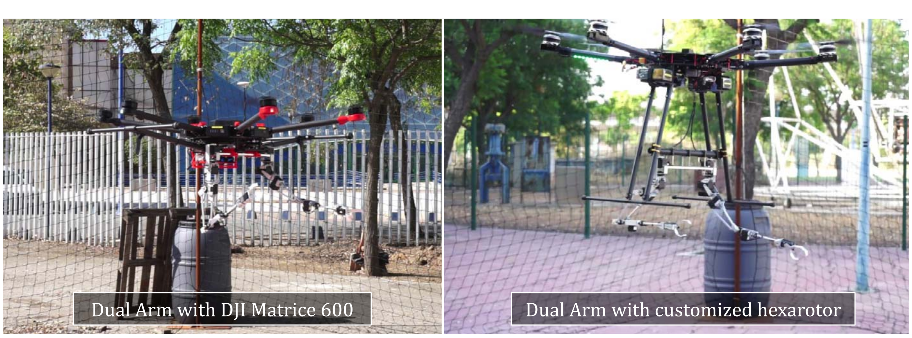

Fig. 1. Developed lightweight and human-size dual arm manipulator integrated in two hexarotor platforms. Outdoor flight tests.