CLF-Based Control for Aerial Manipulation Using Multirotor UAVs

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Abstract— **This paper presents the trajectory-tracking control of a Vertical Take-off and Landing (VTOL) rotorcraft endowing a two Degrees of Freedom (DoFs) manipulator arm. The research considers endogenous (parametric) and exogenous (external disturbances) uncertainties as lumped disturbance, which is estimated via an Extended-State Observer (ESO). A feedback controller is synthesized through the Control Lyapunov Function (CLF) aided by feedforward terms composed of the ESO estimates. The compound system, the rotorcraft, and the manipulator dynamics are mathematically modeled based on the energy-based Euler-Lagrange (EL) formalism. The system's stability is analyzed within the Input-State Stability (ISS) framework, guaranteeing closed-loop stability for the overall design (controller-ESO-UAV+arm). Results from an extensive simulation stage prove the effectiveness of the proposed control strategy.**

I. INTRODUCTION

Aerial manipulation has become an attractive area of research, not only for the scientific community but also for the industry sector. Nowadays, Unmanned Aerial Vehicles (UAVs) are no longer used as passive observers, since they might be capable of performing complex in-flight environment-interactive tasks, including manipulation and physical interaction with the environment [1]. Specific examples of such tasks include oil and gas pipeline monitoring, wind-turbine blades structural inspection, etc. In [2] a novel aerial robotic manipulator for physical contact supervision has been proposed. [3] addresses the design and the implementation of a robot for power line inspection featuring hybrid operation modes. In [4], the physical interaction between an aerial manipulator and canopied trees is investigated.

In order to complete some missions, there are different challenges to overcome: precise positioning, object manipulation, and sensing but, most of all stability. The latest since the dynamics of the aerial robot is significantly altered while shifting and/or carrying payloads. Numerous approaches have been proposed regarding the problem of flight control for aerial manipulation: PID controllers [5], LQR techniques [6], Impedance controllers [7] [8], backstepping techniques [9], Model predictive strategies [10], Bounded control strategies [11], to mention a few.

One of the major difficulties in designing control techniques for interactive systems is the proper knowledge of the system model and its physical parameters. In the concerned problem of rotorcraft and manipulator there are two main modeling methods: the independent modeling method, which divides the system into two independent systems; and the overall modeling method, which considers the composing elements as a multi-body system [12].

As an example of the first approach, [13] considers the manipulator being an external disturbance for the UAV where an H_∞ is proposed for the aerial system as the base for its dynamics. Experimental results validate their approach. Then, [14] extended such work by taking an acceleration feedback term to compensate for potential wind disturbances.

Likewise, for the multi-body method, where modeling is mainly performed through the Euler-Lagrange equations, [15] proposed a hierarchical sliding membrane controller using the inner-outer loop methodology. Simulation experiments validate their approach for trajectory tracking and regulation tasks. [16] presents the modeling and control of an aerial robotic chain manipulator. Experimental results show that the proposed platform might perform complex missions interacting with the environment.

The aforementioned examples corroborate the dependence on system modeling and their complexity due to the presence of non-linearities and parameter uncertainties [17]. In this respect, different approaches propose the design of disturbance observers, as in [18] where a Newton-Euler algorithm is presented to compute the force/moment of the manipulator on the rotorcraft. Then, a Disturbance Observer-Based (DOB) controller was formulated, and experimental results prove the feasibility of the approach. [19] proposed an adaptive sliding-mode disturbance observer (ASMDO)-based control scheme for an aerial manipulator under uncertainties and external disturbances. The performance of the proposed controller was illustrated through a numerical simulation and outdoor experiments. The work in [20], designed a nonlinear observer for an interactive quadrotor. The corresponding algorithm estimates the model uncertainties, to be used later in a Passivity based controller.

Alternatively, to the classical model estimation of uncertainties and external disturbances, the Active-Disturbance Rejection controller (ADRC) aims to reject (estima-

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