Immersion and Invariance Based Trajectory Tracking Control of an Aerial Manipulation System

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ABSTRACT

For aerial manipulators, steady flight must be guaranteed to perform safety interaction with the surrounding environment. This paper focuses on the development of a position control algorithm for an aerial manipulator system (AMS). The position control algorithm is based on the Immersion and Invariance (I&I) theory. The proposed controller maintains the position of the aerial manipulator at the desired point under external an internal disturbances. The control architecture uses the Visual-SLAM technique implemented using on-board sensors for AMS positioning. A series of outdoor experimental tests are performed to demonstrate the effectiveness of the proposed control strategy.

1 INTRODUCTION

The number of applications in which aerial robots are used has grown rapidly over the recent years. Aerial manipulators are designed to perform physical interaction with the surrounding environment. Aerial manipulation research focus on improving mechanical designs, and control strategies to increase the capability to manipulate objects, exert force on a surface and use tools in realistic applications [1]. However, technological challenges still need to be addressed before reliable use of such technology becomes possible. Among these challenges, the capability to carry on a manipulator, and handle disturbances during the movement of the manipulator is still a difficult challenge for small-size UAVs but represents an interesting research topic, and is the driving goal of this work.

The quadrotor is considered one of the most efficient UAV system for researchers around the world in the aerial manipulation field [2]. Due to the higher maneuvering capabilities of the quadrotor in comparison with other UAVs. A small-size quadrotor is capable of loading a light-weight manipulator and maintain a stable flight with a proper control algorithm [3].

The quadrotor is a nonlinear, open-loop, unstable, and underactuated system and the incorporation of a moving robotic arm to the structure increases the disturbance to the system that cannot be easily eliminated by feedback controllers. In order to tackle such problems and to improve the system performance researchers have proposed a host of advanced control methods to guarantee a stable flight during the manipulation task, including impedance control [4, 5, 6], Backstepping control [7, 8], and Proportional-Integral-Derivative (PID) control [9, 10] to name a few.

A methodology to design direct and indirect adaptive controllers for nonlinear systems, called Immersion and Invariance (I&I), was proposed in [11]. The I&I method is a control tool based on two classical theories, which are system Immersion and manifold Invariance [12]. The I&I approach captures the desired behavior of the system to be controlled by introducing a target dynamical system. Then, a suitable stabilizing control law is designed to guarantee that the controlled system asymptotically behaves like the target system [13]. Adaptive controllers based on I&I technique for UAV systems were developed in [14, 15] as a control solution to maintain the vehicle stable along the desired trajectory, and in [16] a multi-variable finite-time composite control strategy based on I&I was proposed for a quadrotor under unknown disturbances.

Up to now, the I&I control approaches for aerial systems described in the literature consider the problem of the position stability for the UAV but do not include the application of the I&I approach to improving the performance of an aerial manipulation system during the movement of the manipulator or the interaction phase, and considering for the aerial manipulator from the perspective of proposing one controller to solve the problem. In this paper, the divide and conquer strategy is followed. Thanks to the engineering advances in quadrotor control, there are available in the market aerial vehicles whose position dynamic response to operator inputs can be modeled by first or second order systems. Hence, in this paper, the internal commercial quadrotor controller is updated with an external I&I adaptive control-loop to solve the position control of an aerial manipulator.

The rest of this paper is organized as follows: The previous works of this research which present the development of the aerial manipulator and the Visual SLAM method to operate in outdoor scenarios are presented in section 2. In section 3 we describe the position control strategy based on the I&I theory to maintain the system in the desired position. The experimental set-up and the results of this work are presented in section 4. Finally, the conclusions of the results and a de-

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scription of the future work of this research are presented in section 5.

2 BACKGROUND

Before beginning with the present research work, in this section, we mention a background of the investigation, experiments, and results in the aerial manipulation field we achieved in recent years. At the beginning of of the research, we developed an aerial manipulator based on a Commercial small UAV (parrot bebop-2) with a 2-DOF arm to study the behavior of the system with the added weight and the disturbances of the arm. The manipulator was designed and implemented based on the technical capabilities of the selected aerial platform. Then, when a stable flight was achieved through a computational compensation control, we improve the capabilities of the proposed aerial manipulator implementing an external control-loop based on a Gain-Scheduling (GS) PID control strategy to work with the internal bebop-2 controller and mitigate the disturbances induced by the movement of the 2-DOF arm and the contact with a vertical surface.

Rojas-Perez and Martinez-Carranza presented in [17] an obstacle avoidance system based on the Visual SLAM approach to estimate the position of a bebop-2 taking advantage of the on-board camera, and without any other motion capture system to feedback the position of the vehicle. We combined this estimation pose technique with our aerial manipulation system to extend its capabilities to outdoor scenarios where the use of caption motion systems to sensing the pose of the vehicle are limited. Then, we presented a study of the behavior of the system in interaction with a vertical surface in an outdoor environment. To improve the results of previous works we consider the implementation of the I&I as an alternative to the GS-PID external control due to the capability to increase the robustness of a nonlinear system against disturbances [11]. In the following section, we present the I&I methodology and the implementation of our aerial manipulation system.

3 THE IMMERSION AND INVARIANCE CONTROL STRATEGY

The use of the I&I approach for stabilization of nonlinear system was presented in [11]. Before explaining the implementation of this research, we briefly recall the fundamental conditions for the standard I&I controller design. Consider the following system:

$$\dot{x} = f(x) + g(x)u \tag{1}$$

with state $x \in \mathbb{R}^n$ and control $u \in \mathbb{R}^m$, with an equilibrium point $x_* \in \mathbb{R}^n$ to be stabilized. Let $p < n$ and assuming existence of mappings $\alpha(\cdot) : \mathbb{R}^p \to \mathbb{R}^p, \pi(\cdot) : \mathbb{R}^p \to \mathbb{R}^n, c(\cdot) : \mathbb{R}^p \to \mathbb{R}^m, \phi(\cdot) : \mathbb{R}^n \to \mathbb{R}^{n-p}, \psi(.,.) : \mathbb{R}^{nx(n-p)} \to \mathbb{R}^m$ such that:

The system (target system):

$$\dot{\xi} = \alpha(\xi) \tag{2}$$

With $\xi \in \mathbb{R}^p$ has a globally asymptotically stable equilibrium at $\xi_* \in \mathbb{R}^p$ and $x_* = \pi(\xi_*)$. (Immersion condition) For all $\xi \in \mathbb{R}^p$

$$f(\pi(\xi)) + g(\pi(\xi))c(\xi) = \frac{\partial \pi}{\partial \xi}\alpha(\xi) \tag{3}$$

(Implicit manifold) The following set identity holds:

$$x \in \mathbb{R}^n \mid \phi(x) = 0 = x \in \mathbb{R}^n \mid x = \pi(\xi), \xi \in \mathbb{R}^p \tag{4}$$

(Manifold attractivity and trajectory boundedness) The system:

$$\dot{z} = \frac{\partial \phi}{\partial x}(f(x) + g(x)\psi(x, z)) \tag{5}$$

With state z, has a globally asymptotically stable equilibrium at zero uniforly in x. Further, the trajectories of the system

$$\dot{x} = f(x) + g(x)\psi(x, z) \tag{6}$$

are bounded for all $t \in [0.\infty)$ Then, x_* is a globally asymptotically stable equilibrium of the closed loop system $\dot{x} = f(x) + g(x)\psi(x, \phi(x))$.

The result summarized above lends itself to the following interpretation. Given the system 1 and the target dynamical system 2 find, if possible, a manifold $\mathcal{M}$, described implicitly by $\{x \in \mathbb{R}^n \mid \phi(x) = 0\}$, and in parameterized form by $\{x \in \mathbb{R}^n \mid x = \pi(\xi), \xi \in \mathbb{R}^p\}$, which can be rendered invariant and asymptotically stable, and such that the (well defined) restriction of the closed loop system to $\mathcal{M}$ is described by $\dot{\xi} = \alpha(\xi)$. Notice, however, that we do not propose to apply the control $u = c(\xi)$ that renders the manifold invariant, instead we design a control law $u = \psi(x, z)$ that drives to zero the off-the-manifold coordinate z and keeps the system trajectories bounded. (For the methodology proof, see [11]).

3.1 Application to an Aerial Manipulation system

Aerial vehicle's internal autopilots shape the system's response at different levels depending on the available sensors. Hence, if rotational states are measured, the internal autopilot can shape the aerial vehicle's response as a second-order system. If, in addition, the translational states are measured, the aerial vehicle can commanded to behave as a first-order system. This is the case of the aerial vehicle used in this work. Using the information from the Attitude Reference and Hedging System as well as optical flow and SLAM algorithms, the internal controller shapes the aerial vehicle as a first-order dynamics expressed by

$$\frac{dx}{dt} = u_\theta + \delta \tag{7}$$

We can assume that our aerial manipulation system can be represented by equation 7. The experimental validation of this model is presented in the following section. δ represents the disturbance of the robotic arm, the wall effect, the interaction with a surface, or any other disturbance. Now, we describe the steps to implement the I&I control strategy to the proposed aerial manipulation system. We first defined the estimation error as

$$\tilde{\delta} = \delta - \rho + \beta(x) \tag{8}$$

where $\tilde{\delta}$ is the estimation error. The time derivative of the estimation error gives

$$\frac{d\tilde{\delta}}{dt} = -\frac{d\rho}{dt} + \frac{\partial\beta}{\partial x}\left(u_\theta + \delta\right) \tag{9}$$

Replacing δ from

$$\frac{d\tilde{\delta}}{dt} = -\frac{d\rho}{dt} + \frac{\partial\beta}{\partial x}\left(u_\theta + \tilde{\delta} + \rho - \beta\right) \tag{10}$$

Now, the dynamics of the estimator' state is defined in terms of known signals as follows

$$\frac{d\rho}{dt} = \frac{\partial\beta}{\partial x}\left(u_\theta + \rho - \beta\right) \tag{11}$$

Substituting (11) in (10) one gets

$$\frac{d\tilde{\delta}}{dt} = \frac{\partial\beta}{\partial x}\tilde{\delta} \tag{12}$$

To ensure that the estimator error converges to zero, one selects $\beta(x) = \Gamma x$, with Γ a positive constant, thus,

$$\frac{d\tilde{\delta}}{dt} = -\Gamma\tilde{\delta} \tag{13}$$

To compensate the disturbance, the following controller is proposed

$$u_\theta = -k_p(x_d - x) - \rho + \beta(x) \tag{14}$$

where $\tilde{x} = x - x_d$ with x_d the desired constant reference, this is,

$$u_\theta = -k_p(x_d - x) - \rho - \Gamma x \tag{15}$$

moreover,

$$\frac{d}{dt}\rho = -\Gamma(\rho + \Gamma x) \tag{16}$$

The closed-loop dynamics reads as

$$\begin{aligned} \frac{d\tilde{x}}{dt} &= -k_p\tilde{x} + \tilde{\delta} \\ \frac{d\tilde{\delta}}{dt} &= -\Gamma\tilde{\delta} \end{aligned} \tag{17}$$

Hence, for any positive gains k_p, Γ, the error signals $\tilde{x}$ and $\tilde{\rho}$ converge to zero. Thanks to the quadrotor symmetry, the controller for the y position is designed following exactly the same procedure. The control law expressed by equations (14)-(16) are implemented in the aerial manipulator to control the longitudinal and lateral motions of the system to regulate the position in an outdoor scenario and guarantee a stable flight. In the next section, we describe the setup of the experiments to investigate the effectiveness of the proposed control strategy.

4 EXPERIMENTS AND RESULTS

4.1 System Behavior

To validate the assumption that the proposed aerial manipulator can be modeled as a first or second order system, a set of tests were developed to investigate the response of the system to an input signal. First, the bebop-2 was tested to prove that the internal controller works efficiently. Then, we repeated the experiment with the same signal but now with the robotic arm attached to bebop-2 to compare the influence of the robotic arm in the system. Figure 1 shows the sequence of movements the system performs in each experiment when the input signal is sent to the vehicle.

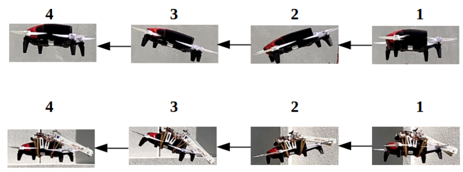

Figure 1: Sequence of movements. Response of the system to input signal.

Several tests were carried out to obtain a mean result of the behavior of the system in both experiments. Figure 2 shows the most representative results in the first experiment.

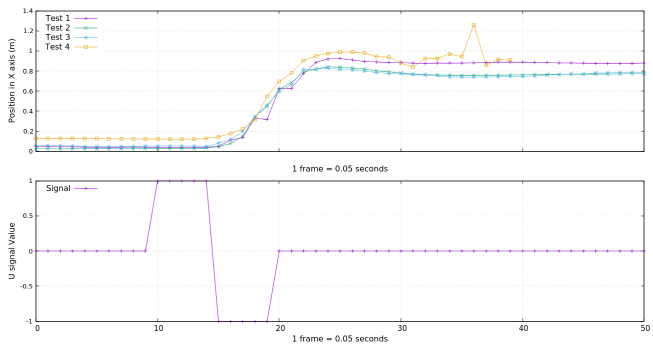

Figure 2: Behavior of bebop-2. Response to input signal.

The results of the second experiment are shown in Figure 3, as in the first experiment a set of tests were carried out. The most representative results of the behavior of the aerial manipulator to the test signal are presented in the graphic. According to the results shown in the graphics, we proved the system behaves as a firs order system even with the robotic arm attached to the structure. therefore, we can assume our proposed aerial manipulator can be described by equation 7

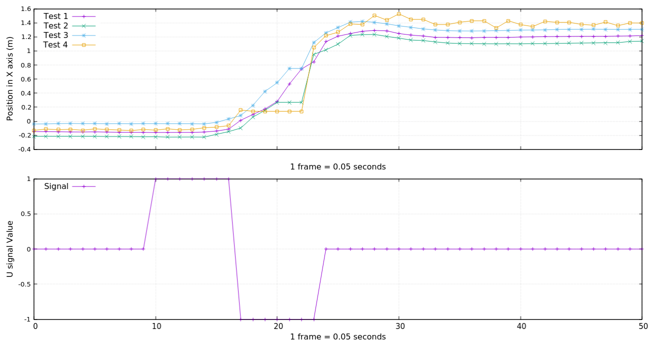

Figure 3: Behavior of the aerial manipulator. Response to input signal.

4.2 Experimental Setup

The proposed control strategy was proved via experimental tests in an outdoor environment. To reduce the disturbances (mostly the disturbances due to the environment) an I&I controller was implemented and added to the system. In previous works, we used the VICON camera system to measure the position of the vehicle and feedback the information to the controller [3, 18] but, in outdoor environments, the implementation of VICON is laborious and limited. For that reason, in most recent works we incorporated the Visual SLAM technique to replace the VICON system in the control structure and to improve the capabilities of our proposed system [19]. The pose estimation using visual SLAM was exploited in [17, 20]. The method takes advantage of two characteristics of the aerial vehicle; the on-board camera, and the altitude measurement.

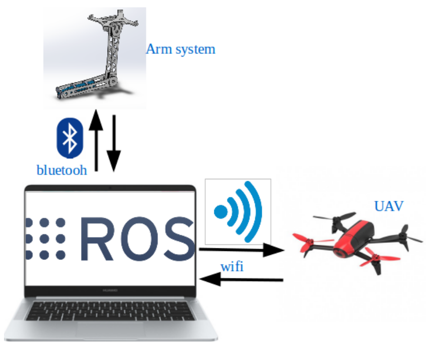

Figure 4: Communication of the complete system.

Due to the features of the aerial platform, we can include the Visual SLAM technique as a pose estimation method in the complete system. Figure 4 shown the communication scheme. The control algorithm runs in a ground station (computer), and we take advantage of the wifi and Bluetooth connection to communicate the computer with the robotic arm and the bebop-2. The coordinate frame of the aerial manipulator is represented by Figure 5. The longitudinal and lateral motions of the system are represented by the X and Z axis. The I&I controller was implemented for both axes, a standard PID controller was also incorporated to control θ and Y axis and guarantee the correct orientation and distance to the ground.

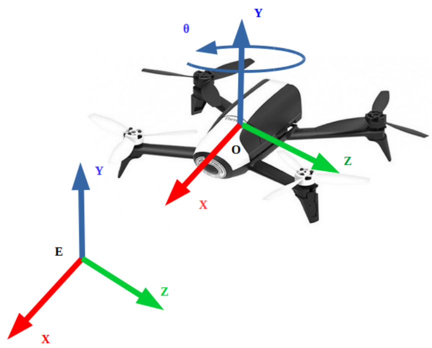

Figure 5: Aerial manipulator scheme.

The outdoor scenario can be shown in Figure 6. In this research work, we decided to put the robotic arm on the top of the vehicle, this allows the sensors below bebop-2 to operate without any kind of obstruction and guarantee a good measurement. This change in the position of the robotic arm also reduces the load because the extension legs are not more needed. The carpet below the aerial manipulator provides visual features which ensure a good performance of the pose estimation method and reduce the pose estimation error.

Figure 6: Outdoor scenario. A carpet is set in the ground to provide more texture for the SLAM technique and improve the pose estimation.

Figure 7 depicts the block diagram for this research. The pose of the system when is in fly mode is provided for the Visual SLAM technique. The movement of the robotic arm to fold and unfold produces a set of different disturbances. The objective of the attitude control is to reduce the displacement produced by this disturbance and any other disturbance induced by the outside conditions to maintain the aerial vehicle in the desired position. The proposed controller operates as external control, calculating the control signal U for the X and Z axis to displace the vehicle to the desired position, then, the U signals are sent to the internal control of Bebop-2. Finally, the pose estimation provides by the Visual SLAM closes the external control loop.

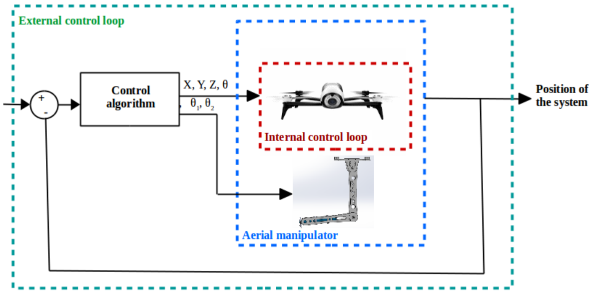

Figure 7: Block diagram of the proposed system.

4.3 Results

Through several experimental tests, we studied the behavior of the system and tuned the parameters k_p and Γ of the control law expressed by equations (14)-(16) to improve the performance of the complete system. In Figure 8 it can be shown the response of the system in the first experiments when the value of the parameters was chosen according to our experience.

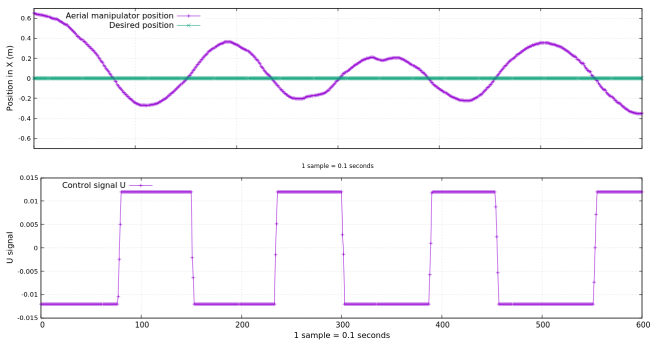

Figure 8: Behavior of the aerial manipulator with the I&I control strategy. First results.

Due to the facility provided by the I&I technique, after a few experiments, we were able to tune the value of the parameters and ensure the system reaches the desired position, and maintain the pose during the disturbances induced by the environment and the robotic arm. Figure 9 shown the results of the final experiments.

5 CONCLUSIONS AND FUTURE WORK

In this work, a control strategy based on immersion and invariance technique has been designed and implemented in

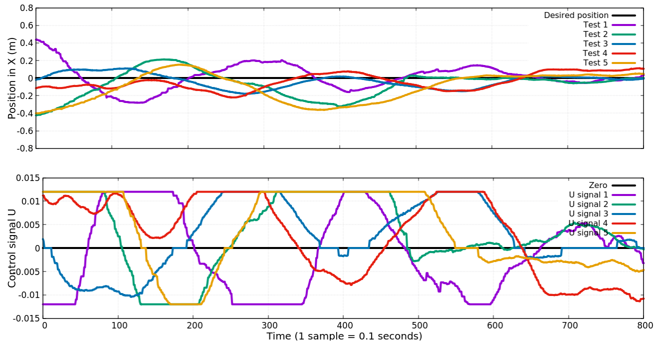

Figure 9: Behavior of the aerial manipulator with the I&I control strategy. Final results.

order to control an aerial manipulator to tackle the issues related to the environment and the movement of the robotic arm. The experimental results obtained for several tests are quite promising. A merit of the proposed algorithm is shown by the equations of the control law which reduced the number of parameters of the controller, simplifying the experimental phase and allowing to obtain an efficient performance of the system. According to the results obtained in this work, we consider that the control can be tested near to a vertical surface and aiming to make contact with the end effector of the arm, this could represent a novel approach for the aerial interaction field.

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