Robotics and Autonomous Systems 62 (2014) 1305–1315

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

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

# Passivity-based adaptive backstepping control of quadrotor-type UAVs[☆]

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## HIGHLIGHTS

- Novel passivity-based adaptive backstepping control of under-actuated quadrotors.
- Demonstrated for the velocity field and trajectory tracking control of the quadrotors.
- Applied for stable haptic teleoperation of the quadrotor over the Internet.

## ARTICLE INFO

*Article history:*
Available online 13 April 2014

*Keywords:*
Adaptive control
Backstepping
Internet
Passivity
Quadrotors
Teleoperation

## ABSTRACT

We propose a novel unified passivity-based adaptive backstepping control framework for “mixed” quadrotor-type unmanned aerial vehicles (UAVs), which consists of the translation dynamics with thrust force input $\lambda \in \Re$ and the attitude kinematics with the angular velocity input $w \in \Re^3$ evolving on SE(3). We also show how our proposed unified framework can be used for velocity field following, timed trajectory tracking and haptic interaction over the Internet, while also providing a complete stability (or collision avoidance) analysis. Experiments using a real quadrotor and lossy communication (for the teleoperation) are also performed to illustrate the theory.

## 1. Introduction

Unmanned aerial vehicles (UAVs) are promising to achieve many useful applications with the cost associated to the on-board human pilots removed: landscape survey, entertainment and games, surveillance/reconnaissance, remote repair, and precise unmanned attack, to name a few. In particular, quadrotor-type UAVs have recently received much attention, due to its agility, (relative) easiness of control, affordability and availability [1]. Teleoperation of such quadrotors would even further expand the application horizons of this versatile flying robotic platform, particularly when it is required to perform complicated/cognitively-loaded tasks in uncertain/unknown environments [2–4].

In this paper, we propose a novel adaptive backstepping control framework for “mixed” quadrotor-type UAVs [5], which can be modeled as a combination of the translation dynamics in E(3) and the attitude kinematics in SO(3), with the thrust force $\lambda \in \Re$ and the angular velocity $w \in \Re^3$ as the control input. Here, we focus on these “mixed” quadrotors, since: (1) many commercially available UAVs (e.g., Asctec Hummingbird® or Pelican®) often allow for direct control of only its angular velocity, not the angular torque, and (2) it is usually possible to design (low-level) angular torque input (i.e., for attitude dynamics) to duplicate (high-level) angular velocity command for the quadrotor’s fully-actuated rotation dynamics, thereby, can “modularize” rotational control implementation.

This mixed quadrotor, however, is under-actuated with only the 1-degree-of-freedom (DOF) thrust force input $\lambda$ for the 3-dimensional Cartesian dynamics in E(3), although the rotational dynamics in SO(3) is fully-actuated with $w \in \Re^3$. On the other hand, the mass parameter of the quadrotor as regards to the thrust force $\lambda$ in general suffers from some uncertainty, particularly due to many nonlinear effects on the generation mechanisms of $\lambda$.

In this paper, we propose a novel unified passivity-based adaptive backstepping control framework for the mixed quadrotors, where the backstepping technique [6] is used to overcome the quadrotor’s under-actuation, while the parameter adaptation approach to online estimate uncertain mass parameter of the quadrotor [7]. For this, we particularly reveal and utilize a certain passivity

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[☆] Research supported in part by the Korea National Research Foundation (Ministry of Education, Science and Technology) under the Grants 2012-R1A2A2-A01015797 and 2009-0087640, and the US National Science Foundation under the Grant CMMI-0727480.

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http://dx.doi.org/10.1016/j.robot.2014.03.019
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structure inherent to this quadrotor-type UAV. Moreover, we also characterize a class of control actions, which are designed for the fully-actuated point-mass dynamics, yet, still transferable to the under-actuated quadrotors with uncertain mass parameter. This unified class of control actions in fact includes the following two possibly most widely-used control objectives: velocity field following and timed trajectory tracking. We also show how our adaptive backstepping trajectory tracking control can be applied to the recently proposed semi-autonomous teleoperation control architecture in [2] and also provide a complete stability and collision avoidance analysis of the total teleoperation-loop.

Numerous strong control techniques have been proposed for the control of quadrotors or similar systems (e.g., [8–14]). However, they are typically developed for specific control objectives (e.g., trajectory tracking [5,8,9,11,13,14]; path or velocity following [10,13]) and do not aim to provide a unified control synthesis framework or characterize the class of possible control actions as achieved in this paper. Most of the available results for the quadrotor control is also for dynamic quadrotors (i.e., accept thrust force and angular torque input) even if many commercially-available systems are "mixed" quadrotors (i.e., accept thrust force and angular velocity input). In contrast, our proposed adaptive backstepping control framework is derived specifically for these "mixed" quadrotors, thus, applicable to many such commercial quadrotor platforms and also much simpler (and easier to implement) than those control laws developed for dynamic quadrotors (cf., [9,10,14]). Our backstepping control also fully embraces the geometry of SE(3), thus, free from the singularity stemming from SO(3) parameterization (e.g., [11,12]), and on-line adapts the mass parameter of the quadrotors, which turn out to be crucial to maintain desired height in real implementation (cf., [9]).

We also show how to apply our adaptive backstepping control to the recently proposed UAV teleoperation architecture of [2]. For this, we particularly elucidate how to utilize a dynamic-extension like filter to circumvent the problem of using high-order derivatives of the master device's position signal received from the discontinuous Internet for our adaptive backstepping control; provide a complete stability/collision-avoidance analysis including all the control-layers in the teleoperation architecture; and also present new Internet teleoperation experimental results with lossy-communication, all of which were only alluded or missing in [2].

A conference version of this paper is [15]. However, in [15], only the backstepping trajectory tracking control (i.e., result of Section 3.2) was presented with no parameter adaptation and robustness analysis. The current version generalizes the result of [15] to the unified passivity-based adaptive backstepping control design while also characterizes a class of possible control actions, with the trajectory tracking in [15] merely as one example of such. The proof of stability/collision-avoidance for the teleoperation (i.e., Proposition 1) is also completely revised to fully incorporate all the relevant control layers. All new experiments are also performed, particularly those on teleoperation with lossy-communication presented for the first time here.

The rest of this paper is organized as follows. Section 2 presents the modeling of the "mixed" quadrotors. Our unified passivity-based adaptive backstepping control framework for quadrotors is then presented and detailed in Section 3 along with velocity following (Section 3.1) and trajectory tracking (Section 3.2) as examples for that. We then apply our adaptive backstepping tracking control for the problem of haptic teleoperation over the Internet in Section 4. Experimental results are then presented in Section 5. Some concluding remarks are given in Section 6.

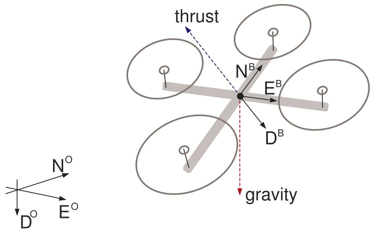

**Fig. 1.** Quadrotor: $\{O\} := \{N^o, E^o, D^o\}$ and $\{B\} := \{N^B, E^B, D^B\}$ are the inertial and body frames, with thrust and gravity along $D^B$ and $D^o$.

## 2. Under-actuated quadrotor-type UAV

We consider the following quadrotor-type UAV, evolving on SE(3) according to the translation dynamics and attitude kinematics [5,13]:

$$m\ddot{x} = -\lambda R e_3 + mge_3 + \delta \tag{1}$$

$$\dot{R} = RS(w) \tag{2}$$

where $m > 0$ is the (uncertain) mass, $x \in \Re^3$ is the Cartesian position expressed in the inertial NED (north-east-down) frame with $e_3$ representing its down-direction, $\lambda \in \Re$ is the thrust along the body-frame down direction, $\delta \in \Re^3$ is the Cartesian disturbance, $R \in SO(3)$ is the rotational matrix describing the orientation of the body NED frame of UAV relative to the inertial NED frame, $w := [w_1, w_2, w_3] \in \Re^3$ is the angular velocity of the UAV expressed in the body NED frame, $g$ is the gravitational constant, and $S(\star) : \Re^3 \to so(3)$ is the skew-symmetric operator defined s.t. for $a, b \in \Re^3$, $S(a)b = a \times b$. See Fig. 1.

Here, we assume that the control inputs for the quadrotor (1)–(2) are the thrust force $\lambda \in \Re$ and the angular velocity $w \in \Re^3$. This "mixed" quadrotor (1)–(2) can capture many commercially available UAVs shipped with a manufacturer's low-level attitude control servo-loop already implemented (e.g. Asctec Hummingbird®). The control inputs $(\lambda, w)$ obtained for these "mixed" quadrotors (1)–(2) can also be applied to the "dynamic" quadrotors (i.e., with translation and attitude dynamics). This is because it is rather straightforward to design the angular torque input $\tau \in \Re^3$ for the dynamic quadrotors to reproduce the target angular velocity $w$, as its rotational dynamics on SO(3) is fully-actuated (e.g., passivity-based control [16]).

The main difficulty of controlling the quadrotor-type UAV (1)–(2) is that it is under-actuated, that is, although the rotation motion can be directly driven by $w \in \Re^3$, its Cartesian dynamics (1) has only 1-DOF thrust input $\lambda$, whose direction is fixed along the down-direction of the UAV's body and can only be controlled via its rotational motion. In Section 3, we will show that, even with this issue of under-actuation and also with uncertainty in the estimate of quadrotor's mass $m$, a fairly large class of control actions, which can be achieved for the simple point-mass dynamics (i.e., $m\ddot{x} = u$), can also be attained for the quadrotor's Cartesian motion (1). For this, we will utilize the backstepping technique [6] along with adaptive control approach [7] to respectively address the issues of the under-actuation and the parametric uncertainty in $m$, while also exploiting a certain passivity property of the under-actuated quadrotors (1)–(2) with some suitably defined input–output pairs.

## 3. Unified passivity-based adaptive backstepping control of quadrotor UAVs

Suppose we want the quadrotor's Cartesian position $x \in \Re^3$ to evolve according to a certain desired control $\nu \in \Re^3$ with the target closed-loop dynamics of $x$ given by

$$m\ddot{x} = \nu(m, x, \dot{x}, t) \tag{3}$$