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A hybrid feedback control strategy for autonomous waypoint transitioning and loitering of unmanned aerial vehicles

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ABSTRACT

We consider the problem of autonomously controlling a fixed-wing aerial vehicle to visit a neighborhood of a pre-defined waypoint, and when nearby it, loiter around it. To solve this problem, we propose a hybrid feedback control strategy that unites two state-feedback controllers: a *transit controller* capable of steering or transitioning the vehicle to nearby the waypoint and a *loiter controller* capable of steering the vehicle about a loitering radius. The aerial vehicle is modeled on a level flight plane with system performance characterized in terms of the aerodynamic, propulsion, and mass properties. Thrust and bank angle are the control inputs. Asymptotic stability properties of the individual control algorithms, which are designed using backstepping, as well as of the closed-loop system, which includes a hybrid algorithm uniting the two controllers, are established. In particular, for this application of hybrid feedback control, Lyapunov functions and hybrid systems theory are employed to establish stability properties of the set of points defining loitering. The analytical results are confirmed numerically by simulations.

1. Introduction

1.1. Background

Autonomous navigation of unmanned aerial vehicles (UAVs) requires algorithms that are capable of accurately controlling the motion of the vehicle with only limited control authority. Such algorithms should be capable of precisely controlling the position, orientation, and velocity of the vehicle by properly generating forces and torques through thrusters, propellers, moving surfaces, etc. A wide range of tasks for such vehicles can be recast as the problem of steering the vehicle to a path given by a closed curve, e.g., a straight line or a loitering pattern. To accomplish such tasks, control algorithms capable of maintaining the vehicle aloft along the given path are required. Recent results in the literature demonstrate that feedback control algorithms can be designed to steer UAVs along different paths by "reshaping" the vector fields that describe the motion of the vehicle under the effect of a guidance law defined by a particular set of differential equations [1,2]. The authors of [2] argue that their reshaping approach is explicit (in the sense that the task to accomplish is pre-defined) and that avoids

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potential complications of trajectory planning and tracking. While performance is not assessed in [2], the performance of tracking control algorithms given in terms of linear, static state-feedback laws deteriorates when curved paths are to be tracked. A study of performance of tracking algorithms was reported in [3], where a nonlinear guidance logic for trajectory tracking of UAVs that overcomes the inherent limitation of linear feedback control in following curved paths is proposed.

An alternative to the vector field shaping technique mentioned above is to rely on multiple controllers, each of them designed to accomplish a different task, and appropriately switch among them. In such approach, a supervisory control algorithm monitors the state of the vehicle and, based on the given mission, determines which controller should be applied at each instant. The switching logic should be capable of "piecing together" the individual controllers to achieve the desired vehicle motion while precluding chattering around the set of points defining the switching condition. While the approach allows independent design of the individual controllers, the emergence of discrete (or discontinuous) dynamics is unavoidable, which may make the analysis more involved (e.g., see the example in [4], which shows that two controllers – a loiter and a transit continuous-time controller – cannot be united using a continuous-time supervisor). Furthermore, the condition triggering the switches between the controllers has to involve memory so as to avoid chattering [5].

Fortunately, recent advances in the literature of hybrid systems have made systematic design of control algorithms piecing together individual controllers possible [6]. Interestingly, the design of such systems can be performed to yield a closed-loop system that not only is chattering-free but also is robust with respect to measurement noise, actuator errors, and external disturbances; see, e.g., [7]. Due to these unique capabilities, the said hybrid systems approach for the combination of multiple controllers has been successfully employed in different applications, such as the stabilization of an inverted pendulum [6] and of the position and orientation of a mobile robot [8]. Furthermore, the technique has been extended in [9] to allow for the combination of multi-objective controllers, including state-feedback laws as well as open-loop control laws. In the context of performance, a trajectory-based approach was also employed in [10] to generate dwell-time and hysteresis-based control strategies that guarantee an input–output stability property characterizing closed-loop system performance. More related to the application studied in this paper, algorithms for vehicles that use multiple controllers coordinated by a supervisory algorithm also lead to a hybrid system and have been proposed in the literature. A review of such works and an algorithm for the control of single and multiple UAVs appeared in [11], where a hybrid automaton with modes corresponding to each control task is proposed and an example of an altitude hybrid controller for a fixed wing UAV is presented. A general formulation of the motion planning problem for dynamical systems with symmetries, which, in particular, includes models of vehicles, appeared in [12], where a general language for trajectory generation using motion primitives; see also its robustification via supervisory hybrid feedback control in [13].

1.2. Contributions

In this paper, we employ the hybrid approach outlined above to provide a solution to the problem of autonomously controlling a fixed wing aerial vehicle to visit a neighborhood of a pre-defined waypoint, and when nearby it, loiter around it without chattering. More precisely, we propose a hybrid feedback control strategy that unites two state-feedback controllers: a *transit controller* capable of steering or transitioning the vehicle to nearby the waypoint and a *loiter controller* capable of steering the vehicle about a loitering radius. Following [14], the aerial vehicle is modeled on a level flight plane with system performance characterized in terms of the aerodynamic, propulsion, and mass properties. The resulting model is nonlinear and with thrust and bank angle being its control inputs. This nonlinear UAV bank-to-turn model partially resembles a ship course controller model [15], where heading is controlled indirectly through the heading rate (it is a variation of the well-known Dubins model). For this vehicle model and employing Lyapunov stability theory, we establish key asymptotic stability properties of the individual control algorithms designed. Both the loiter and transit controllers are designed using the backstepping control design technique [16,17]. With the region of attraction induced by each controller being characterized, the closed-loop system incorporating a hybrid algorithm uniting the individual controllers is shown to be asymptotically stable using stability tools for hybrid dynamical systems. We are not aware of a similar solution for this UAV problem, for which the application of hybrid systems theory leads to a hybrid feedback control algorithm that is chattering-free and with rigorously established properties of the region of attraction.

1.3. Organization of the paper

The remainder of the paper is organized as follows. Section 2 formulates the problem to solve, introduces the model of the vehicle, and proposes the structure of the hybrid controller to be designed. The main results follow in Section 3. This section starts by recasting the problem of interest as a set stabilization problem. Then, it provides the design of the loiter and transit controllers in two steps: first, a controller when actuation is through thrust and heading angle (Section 3.1) and, second, using backstepping, a controller when the actuation is through thrust and bank angle (Section 3.2). In Section 3.3, a hybrid controller combining the two previously designed controllers and the properties it confers to the closed-loop system are presented. In Section 4, the proposed control law and the results are validated in simulations.