Application of Nonlinear Filtering to Navigation System Design Using Passive Sensors

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The problem of navigation system design for autonomous aircraft landing is addressed. New nonlinear filter structures are introduced to estimate the position and velocity of an aircraft with respect to a possibly moving landing site, such as a naval vessel, based on measurements provided by airborne vision and inertial sensors. By exploring the geometry of the navigation problem, the navigation filter dynamics are cast in the framework of linear parametrically varying systems (LPVs). Using this set-up, filter performance and stability are studied in an H_∞ setting by resorting to the theory of linear matrix inequalities (LMIs). The design of nonlinear, regionally stable filters to meet adequate H_∞ performance measures is thus converted into that of determining the feasibility of a related set of LMIs and finding a solution to them, if it exists. This is done by using widely available numerical tools that borrow from convex optimization techniques. The mathematical framework that is required for integrated vision/inertial navigation system design is developed and a design example for an air vehicle landing on an aircraft carrier is detailed.

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I. INTRODUCTION

This work describes a solution to the problem of estimating the relative position and velocity of an autonomous aircraft with respect to a moving platform, such as a naval vessel, using passive sensors. The main motivation for this work stems from the need to develop reliable, miniaturized advanced navigation systems to enable the safe operation of unmanned air vehicles. Economy considerations, together with strict requirements imposed in the course of some envisioned mission scenarios, all but dictate the need to use passive sensors only, thus the emphasis on the integration of vision with other passive sensors such as altimeters and other inertial sensors installed on-board the aircraft.

For previous related work in this area, see [1–4] and the references therein. References [1, 2] describe a solution to the problem of estimating the ground velocity and position of an aircraft based on visual terrain information, whereas [3, 4] focus on the use of GPS and vision based systems for aircraft navigation during night landing. Both papers tackle the problem of navigation system design in the context of extended Kalman filters.

An alternative approach to the navigation system design is proposed here. The problem is formulated in a deterministic setting and relies on the use of special nonlinear filter structures to estimate the relative position and velocity of an aircraft with respect to a moving landing site based on measurements provided by airborne vision and other inertial sensors. The key advantage of this approach is that the resulting nonlinear filters have guaranteed regional stability and performance. Furthermore, it has enabled us to establish a lower bound on the achievable H_∞ filter performance and show that this bound is closely related to positional dilution of precision (PDOP). PDOP is commonly used in science of navigation to characterize the impact of the geometry on the accuracy of the navigation solution.

This work builds on a key result introduced in [5], where a useful property of the so-called perspective projection map is derived and used in the development of a visual estimation system for dexterous manipulation. By using that result and exploring the geometry of the navigation problem at hand, the nonlinear filter dynamics are cast in the framework of linear parametrically varying systems (LPVs) [6]. Using this set-up, filter performance and stability are studied in an H_∞ setting by resorting to the theory of linear matrix inequalities (LMIs) [7]. The design of nonlinear, regionally stable filters to ensure stability and meet adequate H_∞ performance measures is thus converted into that of determining the feasibility of a related set of LMIs and finding a solution to them, if it exists. This is done by using widely available numerical tools that borrow from convex optimization techniques. The mathematical