JOURNAL OF GUIDANCE, CONTROL, AND DYNAMICS
Vol. 32, No. 6, November–December 2009

# In-Flight Trajectory Planning and Guidance for Autonomous Parafoils

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DOI: 10.2514/1.44862

**This paper presents a framework for onboard trajectory planning and guidance for a large class of autonomously guided parafoils. The problem is for the parafoil to reach a given location at a specified altitude with a specified final heading. Through appropriate change of the independent variable, the trajectory planning problem is converted from a three-dimensional free-final-time problem to a two-dimensional fixed-final-time problem. Using the well-known Dubins path synthesis and known parafoil performance parameters, a concept of altitude margin is developed as a quantitative measure of the available maneuvering energy for use in trajectory planning. A hybrid strategy using two methods to generate kinematically feasible fixed-time trajectories is presented, each targeting a different range of initial values of the altitude margin. The trajectory can be replanned onboard in every guidance cycle, making the guidance effectively closed-loop, or replanned whenever the actual deviation of the actual condition from the reference trajectory exceeds a threshold. The proposed planning and guidance algorithm applies to a large class of parafoil canopies and payloads, which encompasses wide variations in the lift-to-drag ratio, wing loading, and maximum turn rate. The guidance logic has the potential of requiring little or no tuning to accommodate variations in canopy performance. Monte Carlo simulations are conducted to evaluate the effectiveness of the algorithm with dispersions in canopy performance, loading, wind profile errors, navigation uncertainty, using lateral control only, and using both longitudinal and lateral control.**

## I. Introduction

AUTONOMOUSLY guided parafoils have many applications including precision airdrop, weapons delivery, remote sensor placement, spacecraft landing, and planetary exploration. Gliding parachutes offer a number of advantages over conventional parachutes including the ability to penetrate wind to reduce landing errors and the ability to deploy the system a significant distance from the target.

The parafoil guidance problem is to generate a trajectory from a given initial configuration (position and heading) $(x_0, y_0, \psi_0)$ at some altitude $h_0$ to a given a terminal position $(x_f, y_f)$ or configuration $(x_f, y_f, \psi_f)$ at some specified final altitude $h_f$. There are many challenges facing any guidance algorithm for autonomous parafoils. Unlike powered vehicles, parafoils generally have no ability to ascend. This means that only one attempt can be made at landing. Most parafoil systems use yaw rate or yaw acceleration as the primary means of control and thus have little or no ability to reduce the along-track trajectory tracking error. Furthermore, the turn response and glide performance can vary greatly depending on canopy size and loading, which may change from mission to mission. Another significant complication is that the wind profile has a profound impact on the motion of the system and is often not known in advance or may only be known approximately. The wind velocity at certain altitudes may exceed the vehicle airspeed, meaning that during certain portions of the flight the system may not be able to make forward progress with respect to the ground. A good guidance algorithm must be robust to all of these adverse conditions. For a given canopy and loading, this is best accomplished by preserving maneuvering energy as long as possible in the trajectory.

There are many applications in which it is desired to minimize the impact force upon landing. This requirement conflicts with the requirement to minimize the landing dispersion resulting from uncertainty in the wind profile. Overcoming wind uncertainty is best accomplished with a higher canopy loading, which increases the system airspeed. The side effect is that both the horizontal and vertical airspeeds are higher, increasing the impact force. Some systems such as the Onyx by Atair Aerospace [1] or the Screamer by Strong Enterprises [2] overcome this problem by using a smaller, higher-loaded, parafoil canopy to track to the target and dissipate excess altitude and then release a secondary nongliding parachute over the target to achieve a soft landing. However, in certain missions the size of the parafoil or the extra weight of the secondary chute may not allow for this approach. In such instances, the alternative is to use a lower canopy loading and land with the vehicle airspeed vector pointed into the wind.

Several algorithms for parafoil guidance, navigation, and control (GNC) are found in the literature. The algorithms generate trajectories that typically fall into one of three categories. Waypoint-based algorithms [3,4] generate a sequence of waypoints to manage excess altitude and have various criteria for exiting the energy management phase and tracking to the target. Maneuver-based algorithms [1] generate a reference glide slope to the target, usually biased from the true system glide slope to allow for wind uncertainty, and perform a sequence of maneuvers to maintain the reference glide slope. Path-based algorithms [5–7] generate a continuous reference trajectory connecting the system position and orientation to the target, and the trajectory is usually parameterized by time or altitude. Other algorithms [8,9] may use a hybrid combination of these

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Presented as Paper 7417 at the AIAA Guidance, Navigation, and Control Conference and Exhibit, Honolulu, HI, 18–21 August 2009; received 10 April 2009; accepted for publication 26 July 2009.

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