Aerobatic Flight for Robotic Fixed-Wing Unmanned Aerial Vehicles

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ABSTRACT

Fixed-wing unmanned aerial vehicles (UAVs) offer significant performance advantages over rotary-wing UAVs in terms of speed, endurance, and efficiency. However, these vehicles have traditionally been severely limited in terms of maneuverability. Through technical advancements in controls and platform design, the Johns Hopkins University Applied Physics Laboratory (APL) is widening the flight envelope for autonomous fixed-wing UAVs.

INTRODUCTION

Fixed-wing unmanned aerial vehicles (UAVs) have long been viewed as valuable assets in both defense and commercial domains. Their endurance and speed make them ideal for gathering information or transporting cargo across open sky. However, for robotics applications where navigation around obstacles is a necessity, fixed-wing vehicles have typically been overlooked in favor of rotary-wing vehicles. Quadcopter UAVs in particular, with their simple mechanical design and high thrust-to-weight ratios, have often been preferred for these applications. This is predominantly because at low speeds and in linear regimes, quadcopters can achieve near-zero turn radii. Fixed-wing UAVs, in contrast, have a fixed (often sizable) minimum turn radius in traditional steady-level flight regimes. At high speeds and in more dynamic regimes, existing simplified differentially flat quadcopter models dramatically reduce the computation time needed to generate feasible trajectories.[1] These simplified models have been shown to work well in practice.[2] Such models do not exist for fixed-wing vehicles traveling at high angles of attack (AoAs); however, regimes with high AoAs are necessary for fixed-wing UAVs to achieve tight turn radii (Figure 1).

Early work in aircraft design and control recognized the value of post-stall maneuvers for increasing aircraft maneuverability.[3] In combat, these high-AoA maneuvers are often viewed as impractical, since they make an aircraft vulnerable by reducing its kinetic energy.[4]

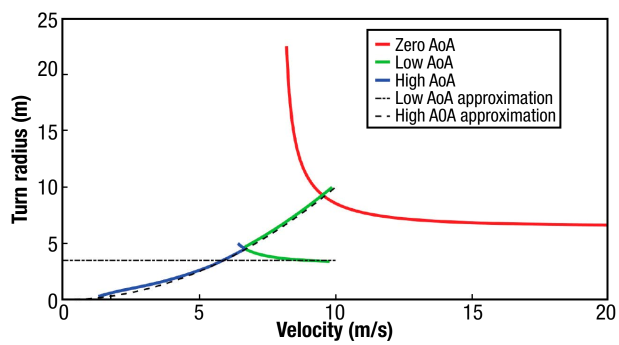

Figure 1. Demonstration of how fixed-wing UAVs achieve smaller turn radii by executing high-AoA maneuvers. Curves were generated by computing turn trim conditions using a nonlinear program and a simplified nonlinear aircraft model without control surfaces. Constraints were placed on the AoA to demonstrate the advantage of post-stall turns.[5]

In the context of mobile robotics, however, these post-stall maneuvers have the potential to dramatically reduce the radius of curvature, allowing a fixed-wing vehicle to navigate through very constrained environments. We believe the tight turning radii that fixed-wing UAVs are capable achieving at high AoAs put these vehicles on par with quadcopter maneuverability and motivate the need for post-stall kinodynamic motion planning strategies.

Figure 2. Time-lapse image showing a small fixed-wing aircraft performing a sharp 90° turn. Two striped poles denote the goal point for the maneuver.[5]

APL-DEVELOPED CONTROL STRATEGY

To achieve real-time planning for fixed-wing vehicles across the entire flight envelope, we implemented a four-stage hierarchical control strategy consisting of a randomized motion planner, a spline-based smoothing algorithm, direct trajectory optimization, and a time varying linear quadratic regulator (TVLQR) for local feedback control. The spline-based smoothed path is used as a seed to the trajectory optimizer and also provides a receding horizon goal point. The local linear feedback controller compensates for model uncertainty.[5]

We demonstrated the efficacy of this approach through a series of hardware experiments using a small foam aircraft (Figure 2). For the experiments, the aircraft was tasked with navigating through a hallway environment, and was given a consistent initial position and velocity using a mechanical launcher. Several trials were also conducted by manually throwing the plane to test the behavior when given imprecise initial conditions. To successfully complete the task, the aircraft needed to plan and precisely execute multiple aggressive turning maneuvers to avoid crashing into the walls. Using our approach, repeatable performance was observed with minimal constraint violation (Figure 3). The algorithm also proved robust to variations in initial conditions, as shown by the paths from the hand-launched trials.

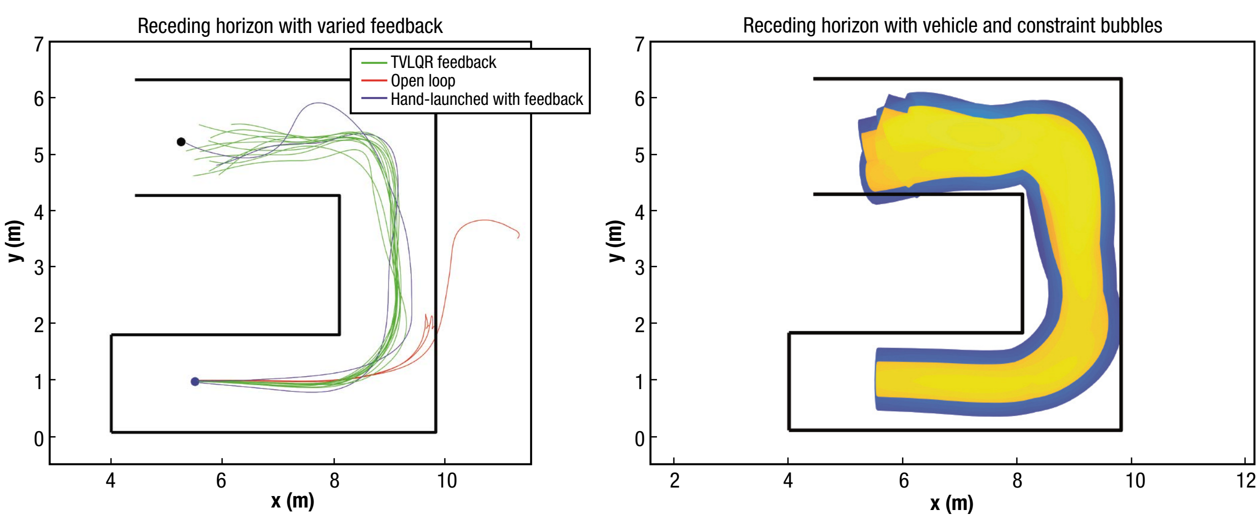

Figure 3. Results of control experiments showing autonomous navigation through a hallway environment. Using our motion planning approach, the aircraft consistently reached the desired goal point (black) while avoiding collision with the walls. Right, the blue region shows the inflated constraint radius around the vehicle, while the yellow region shows the effective vehicle radius. Minor constraint violations are observed at the end of the maneuver, but the vehicle still remains collision free.[5]

FLYING FISH

Under the same guiding motivation, a parallel branch of research led to the development of an autonomous fixed-wing aerial-aquatic vehicle that can transition between water and air (Figure 4). Spawned and created at APL, the Flying Fish is capable of propulsion and control both underwater and in the air using a single speed-controlled propeller. Vehicles like the Flying Fish might be especially well suited to sampling or sensing a landlocked body of water at a distance. In this case, the energetics of the vehicle would be highly advantageous over rotorcraft if the vehicle is required to travel long distances at high altitudes before diving down into a body of water and executing its mission. Another use case could be sparsely sampling a large body very quickly, as might be desired when executing mine countermeasures. Using a fixed-wing aerial-aquatic vehicle could greatly improve endurance if the distances between sample points are large.

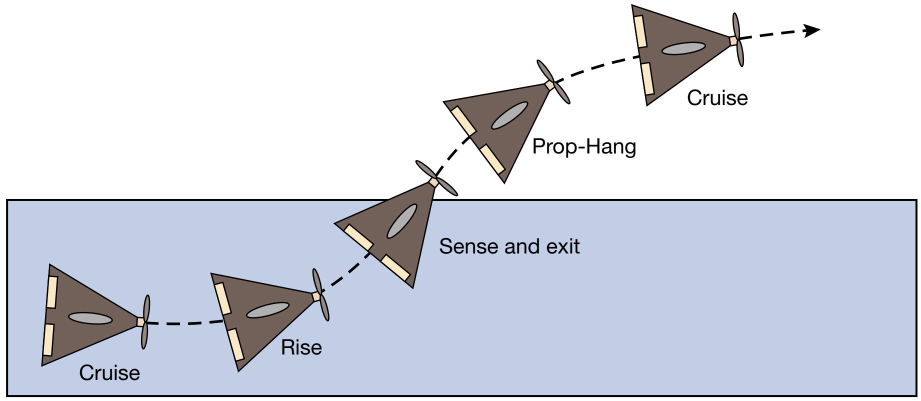

Figure 4. Diagram of flight behavior during a water-exit maneuver. Real-time state estimation is used to detect the transition point as the vehicle exits the water.

Figure 5. Time-lapse image of a successful water-exit maneuver. The Flying Fish approach, combined with onboard state estimation to detect transitions between dynamics regimes, enables the vehicle to autonomously exit a body of water and enter forward flight.

The novel platform design was combined with an autonomous control strategy composed of a hybrid dynamics model, multidomain trajectory optimization, and a closed-loop feedback policy. This approach, combined with onboard state estimation to detect transitions between dynamics regimes, enables the Flying Fish to autonomously exit a body of water and enter forward flight (Figure 5).

CONCLUSION

Overall, these efforts show great strides in bridging the gap between fixed-wing and rotorcraft agility. Through our advancements in control algorithm and platform design, we are demonstrating that fixed-wing UAVs can be made to autonomously perform incredible feats. These results reveal possibilities for new types of missions requiring the endurance and speed advantage of these platforms without sacrificing close-quarters maneuverability.

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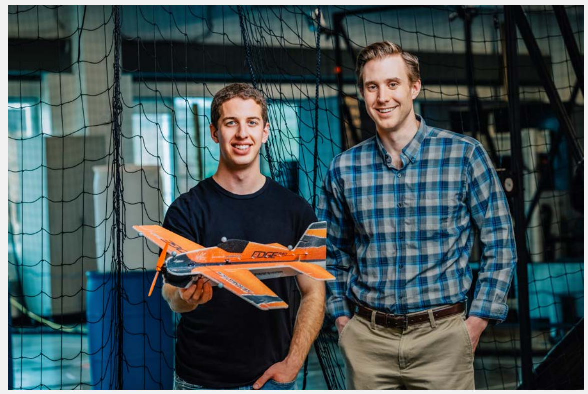

Max R. Basescu (left) and Joseph L. Moore (right)