Flying Between Obstacles with an Autonomous Knife-Edge Maneuver

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Avian flight far exceeds our best aircraft control systems. We have conducted a series of experiments at the Concord Field Station demonstrating the extraordinary maneuverability of the common pigeon, showing it darting through tight spaces and recovering from large disturbances with ease. Our goal is to understand how to make small fixed-wing aircraft achieve similar feats in equally challenging environments.

In the past few years, quadrotor vehicles have succeeded in demonstrating some of these feats, including flying through small gaps, cooperative grasping, transport, and formation flight [6]. Interactions include juggling between themselves in flight [7], cooperative ball throwing [8], and even aerial construction [4].

Fixed-wing performance has been more limited. With longer endurance, fixed wings are often more practical than quadrotors for field operations. They suffer, however, from substantially less control authority compared to the considerable thrust vectoring capabilities of quadrotor platforms. Recently, Cory demonstrated a fixed-wing glider perching on a wire [3]; we apply a similar control design here. Sobolic developed a system capable of transition from the hover regime to forward flight [9]. Bry et. al. maneuvered in tight spaces, but their system was primarily designed to study sensing and did not attempt aggressive obstacle avoidance [2]. Mejias et. al. discuss collision avoidance for aerial tracking, focusing on UAV integration into commercial airspace [5].

In this experiment, we assume that our system is given full sensing information about its location and the environment. The task we execute is a "knife-edge" maneuver, in which a 28-inch wingspan aircraft is launched at 7 meters per second (16 MPH) and must execute a dramatic roll to navigate through a gap that is smaller than its wingspan. This task forces our system to roll 70 degrees in under two body-lengths while maintaining precise tracking following a 9-G launch that accelerates the aircraft to 10 body-lengths per second.

Approach

We use a model-based approach with a 12-state model similar to [9], identified using airframe measurements and repeated flights in motion capture. The motion capture data allows us fit parameters such as body drag that would typically require wind-tunnel testing. Based on that model, we use a locally optimal direct collocation method for trajectory optimization with added non-collision constraints. We stabilize those open-loop plans with a time-varying linear quadratic regulator (TVLQR) [10].

The system's tracking is sufficient for repeated flights through the obstacle field without collision. We have successfully flown 9 out of 9 flights through vertical obstacles spaced 27.5 inches apart using two different locally optimal trajectories. More information about our techniques is detailed in [1].

We have demonstrated a fixed-wing aircraft that successfully performs a knife-edge maneuver required to avoid environmental obstacles, rolling 70 degrees in under two body-lengths, while moving at over 10 body-lengths per second. Our system, using an aerodynamic model, direct collocation based trajectory optimization, and TVLQR is capable of performing the maneuver robustly. To the best of our knowledge, this is the tightest wingspan to gap-size ratio ever navigated with an autonomous fixed-wing aircraft.

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References

[1] A. J. Barry. Flying between obstacles with an autonomous knife-edge maneuver. Master's thesis, Massachusetts Institute of Technology, Sep 2012.

[2] A. Bry, A. Bachrach, and N. Roy. State estimation for aggressive flight in gps-denied environments using onboard sensing. In *2012 IEEE International Conference on Robotics and Automation (ICRA)*, pages 1–8. IEEE, 2012.

[3] R. Cory and R. Tedrake. Experiments in fixed-wing UAV perching. In *Proceedings of the AIAA Guidance, Navigation, and Control Conference*. AIAA, 2008.

[4] Q. Lindsey, D. Mellinger, and V. Kumar. Construction with quadrotor teams. *Autonomous Robots*, 33(3):323–336, 2012.

[5] L. Mejias, S. McNamara, J. Lai, and J. Ford. Vision-based detection and tracking of aerial targets for uav collision avoidance. In *Intelligent Robots and Systems (IROS), 2010 IEEE/RSJ International Conference on*, pages 87–92. IEEE, 2010.

[6] D. Mellinger, N. Michael, and V. Kumar. Trajectory generation and control for precise aggressive maneuvers with quadrotors. In *Proceedings of the 12th International Symposium on Experimental Robotics (ISER 2010)*, 2010.

[7] M. Muller, S. Lupashin, and R. D'Andrea. Quadrocopter ball juggling. In *Intelligent Robots and Systems (IROS), 2011 IEEE/RSJ International Conference on*, pages 5113–5120. IEEE, 2011.

[8] R. Ritz, M. W. Muller, M. Hehn, and R. D'Andrea. Cooperative quadrocopter ball throwing and catching. In *Intelligent Robots and Systems (IROS), 2012 IEEE/RSJ International Conference on*, pages 4972–4978. IEEE, 2012.

[9] F. M. Sobolic. Agile flight control techniques for a fixed-wing aircraft. Master's thesis, Massachusetts Institute of Technology, Department of Aeronautics and Astronautics, Cambridge MA, June 2009.

[10] R. Tedrake. LQR-Trees: Feedback motion planning on sparse randomized trees. In *Proceedings of Robotics: Science and Systems (RSS)*, page 8, 2009.