The 2009 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 11-15, 2009 St. Louis, USA

Stanford Testbed of Autonomous Rotorcraft for Multi-Agent Control

Gabriel M. Hoffmann, Steven L. Waslander, Michael P. Vitus, Haomiao Huang
Jeremy Gillula, Vijay Pradeep and Claire J. Tomlin

***Abstract*— The Stanford Testbed of Autonomous Rotorcraft for Multi-Agent Control, a fleet of quadrotor helicopters, has been developed as a testbed for novel algorithms that enable autonomous operation of aerial vehicles. The testbed has been used to validate multiple algorithms such as reactive collision avoidance, collision avoidance through Nash Bargaining, path planning, cooperative search and aggressive maneuvering. This article briefly describes the algorithms presented and provides references for a more in-depth formulation, and the accompanying movie shows the demonstration of the algorithms on the testbed.**

I. INTRODUCTION

Quadrotor helicopters have become increasingly popular as unmanned aerial vehicle (UAV) platforms. These vehicles have four identical rotors in two pairs spinning in opposite directions, and possess many advantages over standard helicopters in terms of safety and efficiency at small sizes. Many research groups have begun constructing quadrotor UAVs as robotics research tools [1], [2], [3], [4], [5].

The Stanford Testbed of Autonomous Rotorcraft for Multi-Agent Control (STARMAC) [6] is one of the first successful quadrotor research platforms. Currently comprised of six quadrotor helicopters, STARMAC has been developed as an easy-to-use and reconfigurable proving ground for novel algorithms for multi-agent applications.

The vehicle, shown in Figure 1, was designed to be as light as possible, while maintaining sufficient stiffness to ensure accurate state measurement and control actuation. The entire frame weighs approximately 150g, or less than 15% of the total mass of the vehicle in its lightest configuration. The thrust is provided by Axi 2208 brushless motors, Wattage 10×4.5 Park Flyer props (both tractor and pusher), and Castle Creations Phoenix 25 speed controllers, resulting in up to 800g of thrust per motor for a total max gross thrust of 3.6kg. In practice, this is sufficient thrust for the vehicle to operate effectively at up to 2.5kg of total mass, as some thrust margin is required to actuate control commands effectively.

The vehicle is equipped with three separate sensors for full state estimation. A Microstrain 3DMG-X1 IMU provides three-axis attitude, attitude rate and acceleration. The resulting attitude estimates are accurate to $\pm 2^o$, so long as sustained accelerations are not maintained. Height above the ground is determined using the Senscomp Mini-AE (10m range, 100g) sonic ranging sensor which has an accuracy of $3-5$cm. Three-dimensional position and velocity measurements are obtained using carrier phase differential GPS with the Novatel Superstar II GPS unit. Custom code was developed in house that provides a position accuracy of $1-2$cm relative to a base station at 10Hz.

Computation and control are managed at two separate levels. The low level control, which performs real-time control loop execution and outputs PWM motor commands, occurs on an Atmega 128 processor. The high level planning, estimation and control occurs on either a lightweight Gumstix Verdex, a PXA270 based single board computer (SBC) running embedded Linux, or on an Advanced Digital Logic ADL855 PC104+ running Linux. Communications are managed over 802.11g wireless for both configurations of high level computation. The baseline configuration results in a takeoff weight of 1.1kg with the Gumstix, and 1.6kg with the PC104. Vehicle flight times are in the range of $15-20$ minutes. Therefore, the vehicle is able to carry additional payload such as laser range finders and cameras.

Gabriel M. Hoffmann is a Researcher at Palo Alto Research Center. email: gabe.hoffmann@parc.com

Steven L. Waslander is an Assistant Professor in the Department of Mechanical and Mechatronics Engineering at the University of Waterloo. email: stevenw@uwaterloo.ca

Michael P. Vitus and Haomiao Huang are PhD. candidates in the Department of Aeronautics and Astronautics at Stanford University. Email: vitus,haomiao@stanford.edu

Jeremy Gillula is a PhD. candidate in the Department of Computer Science at Stanford University. email: jgillula@stanford.edu

Vijay Pradeep is a Systems Engineer at Willow Garage. email: vpradeep@willowgarage.com

Claire J. Tomlin is a Professor in Electrical Engineering and Computer Sciences at University of California at Berkeley. email: tomlin@eecs.berkeley.edu

Fig. 1. The STARMAC II autonomous quadrotor helicopter in flight.

II. REACTIVE COLLISION AVOIDANCE WITH REACHABLE SETS

The algorithm formulated in [7] uses a rule-based approach derived using optimal control and reachability analysis. It provides collision avoidance, or acts as an added layer of safety, for higher level logic. The goal is to be minimally invasive and only affect control inputs when required to avoid collision. Two control laws were developed, one for two vehicles, and one for n_v vehicles. In both, the vehicles compute analytical avoid set boundaries with respect to each other vehicle. When any vehicles are on the boundary of their avoid sets, collision avoidance action is taken. In the two vehicle scheme, a boundary is computed using optimal control that is proven safe analytically. In the n_v vehicle scheme, pairwise avoid sets can be computed through linear algebra. The control law is developed with safety proven analytically for three vehicles, and validated for $n_v > 3$ in simulation. The computational complexity of the algorithm is $O(n_v)$.

In the movie, two pilots are manually controlling the quadrotors attempting to cause a collision but the software is intervening to maintain safety.

III. Decentralized Collision Avoidance via Nash Bargaining

In [8], the problem of collision avoidance between vehicles with pre-defined desired trajectories is considered. This work developed a receding horizon algorithm that enforces collision avoidance constraints on a team of cooperative vehicles in a decentralized manner. The collision avoidance problem is formulated as a nonlinear, nonconvex optimization program, and the decentralized coordination algorithm with the Nash Bargaining cost metric is applied with local neighborhoods defined by a maximum communication radius for each vehicle. A decentralized penalty method is also developed to solve this problem formulation.

By selecting the Nash Bargaining solution as the cost metric, a balance is struck between efficiency and fairness of the solution, and through the decentralized penalty method, the need for an initial feasible solution and the need for any central coordination are avoided.

IV. Tunnel-MILP Path Planning

The Tunnel-MILP algorithm [9], [10] is a novel three-stage path planning method for known obstacle positions that attempts to address the scalability of the mixed integer linear program (MILP) formulation. In the first step, a desirable preliminary path is planned through the environment ignoring the vehicle's dynamics. Second, an obstacle free tunnel is formed around the pre-path as a sequence of convex polygons through which the vehicle must travel. Finally, a dynamically feasible trajectory is generated using a MILP formulation that restricts the vehicle to stay within the pre-defined tunnel. Simulation results for this approach were performed and revealed a significant increase in the size and complexity of the environment that can be solved.

V. Mobile Sensor Network Control using Mutual Information Methods and Particle Filters

In [11], [12], a set of methods was developed that enable an information-theoretic distributed control architecture to facilitate search by a mobile sensor network. This technique exploits the structure of the probability distributions of the target state and of the sensor measurements to control the mobile sensors such that future observations minimize the expected future uncertainty of the target state. The mutual information between the sensors and the target state is computed using a particle filter representation of the posterior probability distribution, making it possible to directly use nonlinear and non-Gaussian target state and sensor models. Monte Carlo results demonstrate that as network size increases, the sensors more quickly localize the target. The proposed methods are shown to produce similar results to linearized methods in particular scenarios, yet they capture effects in more general scenarios that are not possible with linearized methods.

VI. Control of Autonomous Quadrotor Helicopters in Aggressive Maneuvering

The work presented in [13], which is not shown in the accompanying movie, extended previous analysis on several important aerodynamic effects impacting quadrotor flight in regimes beyond nominal hover conditions. The implications of these effects on quadrotor performance were investigated and control techniques were developed that compensate for them. The analysis of blade flapping and thrust variation were applied to the creation of models and control techniques for operating a quadrotor at high speeds and under aggressive maneuvers. Simulations of a quadrotor were performed including these effects and validated against actual flights on the STARMAC quadrotors. A novel feedback linearization controller was devised which successfully compensated for these aerodynamic effects. This is the first time such control techniques have been applied to quadrotor helicopters.

References

[1] E. Altuğ, J. P. Ostrowski, and C. J. Taylor, "Quadrotor control using dual camera visual feedback," in *Proceedings of the IEEE International Conference on Robotics and Automation*, (Taipei, Taiwan), pp. 4294–4299, Sept 2003.

[2] S. Bouabdallah, P. Murrieri, and R. Siegwart, "Towards autonomous indoor micro VTOL," *Autonomous Robots*, vol. 18, pp. 171–183, March 2005.

[3] P. Pounds, R. Mahony, and P. Corke, "Modeling and control of a quad-rotor robot," in *Proceedings of the Australasian Conference on Robotics and Automation*, (Auckland, New Zealand), 2006.

[4] M. Valenti, B. Bethke, G. Fiore, J. P. How, and E. Feron, "Indoor multi-vehicle flight testbed for fault detection, isolation, and recovery," in *Proceedings of the AIAA Guidance, Navigation and Control Conference and Exhibit*, (Keystone, CO), August 2006.

[5] S. Craciunas, C. Kirsch, H. Rock, and R. Trummer, "The javiator: A high-payload quadrotor UAV with high-level programming capabilities," in *Proceedings of the 2008 AIAA Guidance, Navigation, and Control Conference*, (Honolulu, Hawaii), 2008.

[6] G. M. Hoffmann, H. Huang, S. L. Waslander, and C. J. Tomlin, "Quadrotor helicopter flight dynamics and control: Theory and experiment," in *Proceedings of the AIAA Guidance, Navigation, and Control Conference*, (Hilton Head, SC), August 2007.

[7] G. M. Hoffmann and C. J. Tomlin, "Decentralized cooperative collision avoidance for acceleration constrained vehicles," in *Proceedings of the 47th IEEE Conference on Decision and Control*, (Cancun, Mexico), December 2008.

[8] S. L. Waslander, *Multi-Agent System Design for Aerospace Applications*. PhD thesis, Stanford University, California, 2007.

[9] M. P. Vitus, S. L. Waslander, and C. J. Tomlin, "Locally optimal decomposition for autonomous obstacle avoidance with the tunnel-MILP algorithm," in *Proceedings of the 47th IEEE Conference on Decision and Control*, (Cancun, Mexico), December 2008.

[10] M. P. Vitus, V. Pradeep, G. M. Hoffmann, S. L. Waslander, and C. J. Tomlin, "Tunnel-milp: Path planning with sequential convex polytopes," in *Proceedings of the AIAA Guidance, Navigation, and Control Conference*, (Honolulu, HI), August 2008.

[11] G. M. Hoffmann, *Autonomy for Sensor-Rich Vehicles: Interaction between Sensing and Control Actions*. PhD thesis, Dept. Aero. Astro., Stanford Univ., Stanford, CA, 2008.

[12] G. M. Hoffmann and C. J. Tomlin, "Mobile sensor network control using mutual information methods and particle filters," *Submitted to IEEE Transactions on Automatic Control*, 2007.

[13] H. Huang, G. M. Hoffmann, S. L. Waslander, and C. J. Tomlin, "Aerodynamics and control of autonomous quadrotor helicopters in aggressive maneuvering," in *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA)*, (Kobe, Japan), May 2009.