Multi-Vehicle Flight Experiments: Recent Results and Future Directions

Jonathan P. How
Massachusetts Institute of Technology
Cambridge, MA, USA 02139

jhow@mit.edu

Abstract

This paper discusses recent flight test results in the Aerospace Controls Laboratory (ACL) at MIT. This includes flight tests using a large team of simple external UAVs and a unique indoor multi-vehicle testbed named RAVEN (Real-time Autonomous Vehicle indoor test Environment). RAVEN is comprised of both aerial and ground vehicles, allowing researchers to conduct tests for a wide variety of long-duration mission scenarios in a controlled environment. A comparison of RAVEN with previous testbeds illustrates the many advantages of this new approach.

1.0 INTRODUCTION

Unmanned aerial vehicles (UAVs) are becoming vital warfare and homeland security platforms because they significantly reduce costs and the risk to human life while amplifying warfighter and first-responder capabilities [1]. These vehicles have been used in Iraq and during Hurricane Katrina rescue efforts with some success, but there remains a formidable barrier to achieving the future vision of multiple UAVs operating cooperatively with other manned and unmanned vehicles in the national airspace and beyond. Numerous researchers are investigating the planning, sensing, and control systems that will enable multiple autonomous agents to cooperatively execute these missions [1,2,3,4]. However, a key step towards transitioning the high-level planning algorithms to future missions is to successfully demonstrate that they can handle similar implementation challenges using scaled vehicles operating in realistic environments. Performing experiments on scaled testbeds will highlight the fundamental challenges associated with: (i) planning for a large team in real-time with computation and communication limits; (ii) developing controllers that are robust to uncertainty in situational awareness, but are sufficiently flexible to respond to important changes; and (iii) using communication networks and distributed processing to develop integrated and cooperative plans.

As discussed in [5], numerous research groups have developed a variety of platforms to verify advanced theories and approaches for UAVs. Many of the multi-UAV platforms are built for outdoor use and examine questions related to autonomous exploration in unknown urban environments or probabilistic pursuit-evasion games [6,7], autonomous coordination and control algorithms [8,9], and other multi-vehicle experiments [10-12]. There are a number of indoor multi-vehicle platforms being used for control and networking research, many of which operate on the ground [13,14,15]. Of the indoor platforms that have developed for flight testing, setups such as [16] required a large area to fly and a significant period of time for setup, but most other indoor flying testbeds operate in constrained three dimensional volumes [17,18].

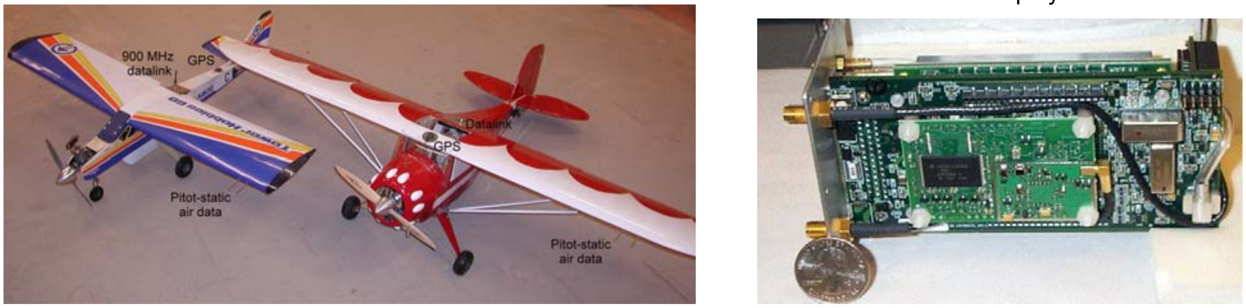
Several testbeds have been designed at MIT ACL to simulate many challenging operational scenarios, with a particular focus on cooperative coordination and control of multiple vehicles for missions such as: low-cost multi-target surveillance and tracking, wide-spread search, and moving target location and tracking. These missions typically require the close coordination and control of many different types of vehicles (e.g., unmanned vehicles {fighters, strike, and electronic suppression}, semi-autonomous UAV's {fixed-wing and helicopters}, surveillance aircraft and satellites, communication vehicles {AWACS}, and ground forces) to accomplish the overall objectives.

The testbeds were designed to reflect the complexity expected in future combat operations and consist of many (semi-) autonomous heterogeneous vehicles. The main design philosophy in the development was to use *simple* vehicles, such as rovers and ARF UAVs with commercial off-the-shelf autopilots, so that *many* of them can be operated at the same time (see Figure 1). This provides a good combination of flexibility, agility, and mobility, and allows us to use the testbeds in a broad range of applications.

While the entire system infrastructure was set up to emulate a fully integrated fleet of UAVs (e.g., using distributed planning and control for the team linked over a dynamic network based on information extracted from onboard sensors), the goal was to maintain as much simplicity as possible in the vehicles themselves, reducing the conservatism that tends to exist for more expensive UAV platforms. As such, all high-level processing is executed off-board using planning computers and all data passes through a central hub that performs data management between the planning computers and vehicles. This central hub is used to simulate delays and outages of the communication between vehicles, emulate additional payload sensors, and detect changes in the environment. Data and commands can be transferred between the planning and vehicle systems at rates of about 1 Hz, providing a sufficiently fast response to any dynamic changes detected in the environment. This setup greatly reduces the logistics required to operate the UAV testbeds, but it still provides the functionality needed to evaluate high-level planning algorithms using information provided by onboard sensors when the vehicles communicate over dynamic networks.

(a) Fleet of eight identical Trainer 60 aircraft used in the multi-UAV testbed at MIT.

(b) Groundstation, Avionics and pilot console for Cloud Cap system.



(c) Trainer 60 and Monocoupe aircraft in the MIT UAV testbed.

(d) Cloud Cap Piccolo autopilot.

Figure 1: Fleet of 8 MIT UAVs that are flown autonomously using a commercially available autopilot from Cloud Cap Technology. See [8,9] for further details.

As examples of the types of experiments performed with the MIT UAV testbed, Figure 2 shows the results of a 22 minute autonomous flight involving two UAVs simultaneously flying the same flight plan. Both vehicles tracked the waypoints in the presence of wind, and open loop formation flight was achieved by adjusting the commanded speed until the vehicles were in phase with one another. A 50 m altitude offset was applied to one of the vehicle trajectories in Figure 2 to allow for easier viewing. As another practical application for timing control, two UAVs were linked to the same receding horizon trajectory planner, and independent timing control was performed along the designed plans. An altitude offset of 20 m was applied to the second vehicle in order to avoid collisions. Again, both vehicles tracked the waypoints in the presence of wind, and formation flight was achieved through autonomous control of the reference airspeed. Figure 2 (right) shows an aerial photo from the onboard camera as the second UAV autonomously overtook the leader and then slowed down to the desired speed.

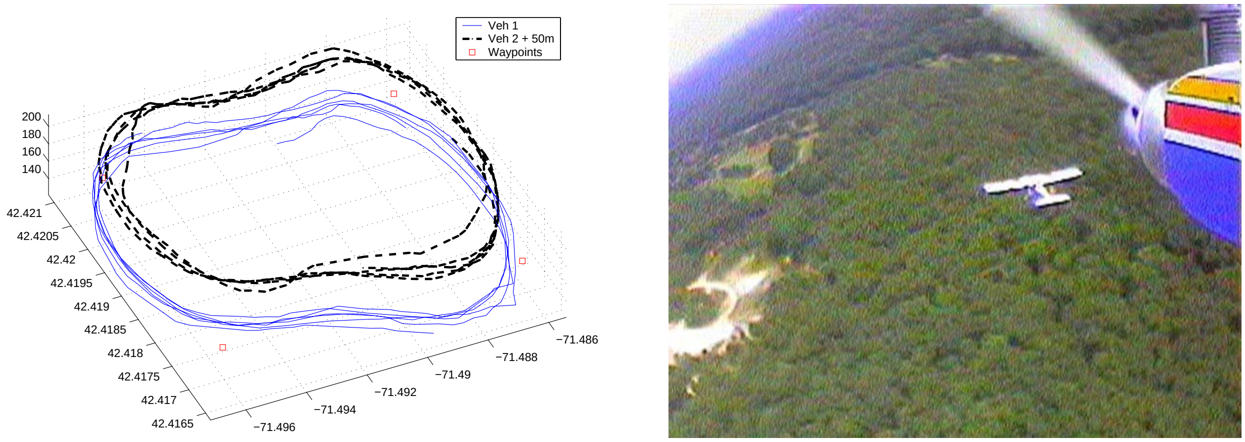


Figure 2: Autonomous UAV flight data. Each vehicle flew the same waypoint plan. The results are shown with a 50 m offset for easier viewing (left). Aerial photo from the onboard camera during the autonomous rendezvous of two aircraft using timing control (right).

Table 1 compares the four testbeds recently developed at MIT to support the ongoing UAV research. This comparison is done in terms of the types of experiments that can be performed, the uncertainty included in these experiments, and the limitations that exist. For example, while tests on the rovers have limited realism, they are a versatile platform for carrying new sensors and they provide an easy way to investigate the performance of new control algorithms with realistic limits on the computation and communication.

The hardware-in-the-loop (HWIL) testbed was primarily designed to test the autopilot settings before flights; however the high fidelity HWIL simulation can also be used to perform detailed experiments of multi-vehicle flights that would otherwise not be possible on the vehicle testbed due to logistical constraints. The HWIL results are realistic because the vehicle and environment models in this simulation were calibrated using experimental flight data, and the planning system interacts with the autopilots exactly as it would if the aircraft were actually flying.

Of course, the UAVs provide the final hardware validation, but due to logistical constraints, the scenarios tend to be quite simple and typical experience is that it is difficult to fly more than two UAVs at the same time (as a rule of thumb, each UAV in the air typically required 3 people on the ground to operate it).

Maintaining all three testbeds is clearly difficult, but, as indicated in Table 1, each plays an important role in evaluating all the aspects of the coordination and control problem (computation, communication, vehicle dynamics, and uncertainty). Furthermore, because the interfaces between the planning system and the vehicles were designed to be identical for all testbeds, it is very easy to transition the control algorithms from one testbed to another, which significantly reduces the logistical problems. The following section discusses the RAVEN testbed in more detail, which, as shown in Table 1, retains many of the advantages of the Multi-UAV testbed without incurring the significant logistics costs.

Table 1: Testbed Comparison.

	Rovers	Autopilot HWIL	Multi-UAV	RAVEN
Experiment Uncertainty	Scenario outcome Communication Computation	Dynamics Disturbances Communication Computation	Dynamics Disturbances Communication Computation	Dynamics Disturbances Communication Computation
Utility	Versatile platform Heterogeneous Complex Scenarios # Vehicles (N ≥ 8)	Full UAV Dynamics Pre-flight Validation Complex Scenarios # Vehicles (N ≥ 8)	Realistic Experiments Sensor Platform Hardware Validation Three dimensional	Realistic Experiments Sensor Platform Hardware Validation Complex 3D Scenarios # Vehicles (N ≥ 10) Any Time Operations
Limitations	Two Dimensional Few Disturbances Simplified Dynamics Moderate Logistics	A simulation	Heavy Logistics Simple Scenarios # Vehicles (N ≤ 3) Day Operations	Room Size

2.0 RAVEN

The many testbeds discussed in the previous section have several limitations that inhibit their utility for investigate questions related to multi-day, multi-agent mission operations. For example, outdoor platforms can be tested only during good weather and since most outdoor UAV test platforms can be flown safely only during daylight operations, these systems cannot be used to examine research questions related to long-duration missions, which may need to run overnight. In addition, many of these vehicles are modified to carry additional vehicle hardware for flight operations. As a result, these vehicles have to be redesigned to meet payload, onboard sensing, power plant, and other requirements. Thus, these vehicles must be flown in specific environmental conditions, unrelated to flight hour constraints, to avoid damage to the vehicle hardware. These external UAVs also typically require a large safety and support team, which makes long-term testing logistically difficult and expensive.

To overcome these limitations, the MIT Aerospace Controls Laboratory has developed a unique indoor multi-vehicle test facility called RAVEN (Real-time indoor Autonomous Vehicle test ENvironment) to study long-duration missions in a controlled environment [5]. The facility is designed to test and examine a wide variety of multivehicle missions using both autonomous ground and air vehicles. A key feature of RAVEN is a global metrology system that yields accurate, high bandwidth position and attitude data for all vehicles in the room. The sensing approach uses the Vicon MX camera system [19] to detect the vehicle's position and orientation in real-time. By attaching reflective balls to the vehicle's structure, the Vicon MX Camera system and Tarsus software can track and compute the vehicle's position and attitude information at rates up to 120 Hz, with a 10 ms delay, and sub-mm accuracy. Just as GPS spurred the development of largescale UAVs, we expect this new sensing capability to have a significant impact on 3D indoor flight, which has historically been restricted to very small volumes.

RAVEN follows the design philosophy used in the previous MIT ACL testbeds in that the team planning and vehicle control commands are processed off-board and sent from the vehicles' control computers to the vehicles using standard R/C transmitters (see Figure 3). Note that the position markers for the sensing system are very lightweight, so the Vicon system can sense position and attitude without adding significant payload to the vehicles. Thus the platform can use small, essentially unmodified, radio-controlled vehicle hardware (e.g., electric helicopters and airplanes) [20]. This enables researchers to avoid overly conservative flight testing, and has enabled us to fly 10 air vehicles at the same time in a typical-sized room.

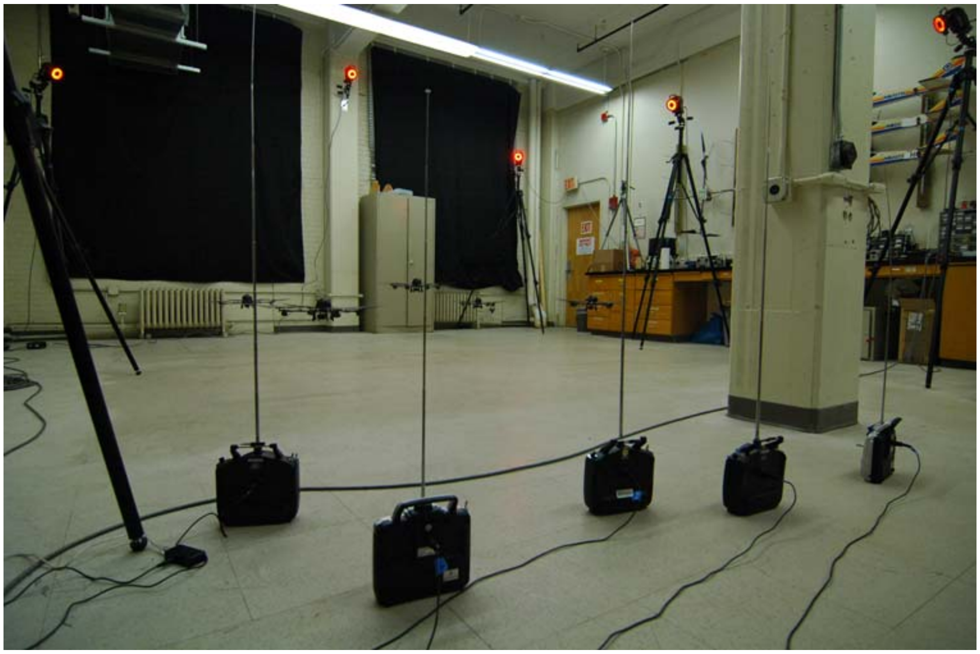


Figure 3: RAVEN infrastructure required to fly five autonomous quadrotors [20]. The bright LED rings show the location of the Vicon cameras. The Vicon data is processed in a central computer and then distributed to the ground flight computers that are dedicated to a particular vehicle. This position data is processed using the current mission plan (developed in a second set of distributed computers), and the signals are sent directly to the UAV's actuators using the RF transmitters.

The RAVEN testbed has proven to be an excellent rapid prototyping environment for UAV research – we have demonstrated advanced path planning concepts [21,22], health management for long-term persistent surveillance missions [23], multi-UAV search and track using onboard vision [24]. It has also been used to support class projects for an MIT graduate-level course on aircraft stability and control.

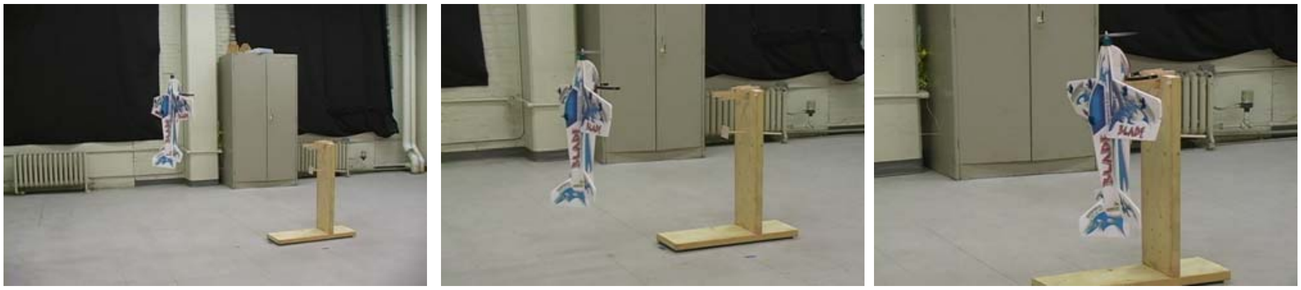
An additional benefit is that one operator can set up the platform for flight testing multiple UAVs in less than 20 minutes, so researchers can perform a large number of test flights in a short period of time with little logistical overhead. Furthermore, since the system autonomously manages the navigation, control, and tasking of realistic air vehicles during multivehicle operations, researchers can focus on the algorithms associated with the team coordination rather than the details of the implementation. These properties greatly enhance the utility of the testbed, making it an effective platform rapid prototyping environment for multi-vehicle mission management algorithms. It is also routine to have a single operator command multiple UAVs during a mission, which is a significant difference from the external testbeds.

Figures 4 and 5 show examples of further rapid prototyping done on aggressive flight manoeuvres using RAVEN with an essentially unmodified foam R/C airplane [25]. The primary objective of this work is to design hybrid nonlinear controllers to execute very agile acrobatics. Figure 4 shows a sequence that illustrates the current capabilities. The aircraft: (a) takes-off vertically and hovers over to the start point, (b) transitions to horizontal flight, (c,d,e) tracks a very tight circular path for three laps, and (f) transitions back to vertical. Similar tests have demonstrated a take-off followed immediately by a transition to hover. The aircraft can also fly over and perch on the landing platform (see Figure 5) [25,26]. These tests have been successfully repeated numerous times and videos are available online at http://vertol.mit.edu.

(a) Manoeuvre in hover (b) Transition to horizontal flight (c) Bank to turn (~70 degs)

(d) Follow circular trajectory (e) Repeat for three laps (f) Transition back to vertical

Figure 4: Autonomous aircraft hover, transition to level flight, and transition back to hover



(a) Hover flight (b) Manoeuvre to landing post (c) Perch on post

Figure 5: Autonomous Airplane Perching Experiment – Airplane commanded to hover and while in hover state, vehicle is commanded to land on vertical landing platform [24]

3.0 CONCLUSION

RAVEN offers government, commercial and academic organizations a low-cost flight test platform for the rapid prototyping of multi-vehicle mission algorithms and vehicle hardware. Since RAVEN is very robust, users can execute multiple missions in a short period of time with minimal setup and organization between tests. Thus, this platform will be a very attractive alternative to the existing testing methods because multi-vehicle tests can be performed using this real-time platform at a fraction of the cost. RAVEN is an impressive facility for multi-vehicle testing — we have only just started to explore its full capabilities.

4.0 ACKNOWLEDGEMENTS

This research has been generously supported by AFOSR Grants F49620-01-1-0453, FA9550-04-1-0458 and DURIP Grant F49620-02-1-0216 and the Boeing Company under the guidance of Dr. John Vian at the Boeing Phantom Works, Seattle, WA. Research also funded in part by AFOSR grant. The author is indebted to the many students that have performed this research, including Luca Bertuccelli, Dr. Arthur Richards, Dr. Yoshi Kuwata, Pete Young, Carl Engel, Dan Harjes, Mario Valenti, Brett Bethke, Daniel Dale, Adrian Frank, James McGrew, Daniel Levine, and Spencer Ahrens.

5.0 BIBLIOGRAPHY

[1] Chandler, P. R., M. Pachter, D. Swaroop, J. Fowler, J. Howlett, S. Rasmussen, C. Schumacher and K. Nygard "Complexity in UAV Cooperative Control", In Proceedings of the *American Control Conference*, Anchorage AK. pp. 1831-1836, 2002.

[2] Office of the secretary of defense. UAS Roadmap Available online (Accessed April 2007), see: *www.acq.osd.mil/usd/Roadmap Final2.pdf*

[3] Butenko, S., R. Murphey and P. Pardalos (Eds.) Recent Developments in Cooperative Control and Optimization, Vol. 3, Kluwer Academic Publishers, 2004.

[4] Kott, A., Advanced Technology Concepts for Command and Control, Xlibris Corporation, 2004.

[5] Valenti, M., Bethke, B., Fiore, G., How, J. P., and Feron, E., *Indoor Multi-Vehicle Flight Testbed for fault Detection, Isolation, and Recovery*, Proceedings of the AIAA Guidance, Navigation, and Control Conference and Exhibit, Keystone, CO, August 2006.

[6] Shim, D., Chung, H., Kim, H. J., and Sastry, S., *Autonomous Exploration in Unknown Urban Environments for Unmanned Aerial Vehicles*. In Proceedings of the AIAA Guidance, Navigation, and Control Conference and Exhibit, San Francisco, CA, August 2005.

[7] Vidal, R., Shakernia, O., Kim, H.J., Shim, H., and Sastry, S., "Multi-Agent Probabilistic Pursuit Evasion Games with Unmanned Ground and Aerial Vehicles" *IEEE Transactions on Robotics and Automation*, Vol. 18, No. 5, 2002, pp. 662–669.

[8] King, E., Kuwata, Y., and How, J. P., "Experimental Demonstration of Coordinated Control for Multi-vehicle Teams," *International Journal of Systems Science*, Vol. 37, No. 6, May 2006, pp. 385-398.

[9] King, E., Alighanbari, M., Kuwata, Y., and How, J.P., "Coordination and Control Experiments on a

Multi-Vehicle Testbed", Proceedings of the IEEE *American Control Conference*, 2004.

[10] Nelson, D. R., Barber, D.B., McLain, T.W., and Beard, R.W., "Vector Field Path Following for Small Unmanned Air Vehicles", Proceedings of the *American Control Conference*, June 2006.

[11] Hoffmann, G., Rajnarayan, D. G., Waslander, S. L., Dostal, D., Jang, J.S., and Tomlin, C., "The Stanford Testbed of Autonomous Rotorcraft for Multi Agent Control (STARMAC)", In the Proceedings of the *23rd Digital Avionics Systems Conference*, Salt Lake City, UT, November 2004.

[12] Johnson E. N., and Schrage, D. P., "System integration and operation of a research unmanned aerial vehicle", AIAA *Journal of Aerospace Computing, Information, and Communication*, Vol. 1, 2004, pp. 5-18.

[13] Z. Jin, S. Waydo, E. B. Wildanger, M. Lammers, H. Scholze, P. Foley, D. Held, and R. M. Murray, "MVWT-11: The second generation Caltech multi-vehicle wireless testbed", Proceedings of the *American Control Conference*, Boston, MA, June 2004, pp. 5321-5326.

[14] Vladimerouy, V., Stubbs, A., Rubel, J., Fulford, A., Strick, J., and Dullerud, G., "A Hovercraft Testbed for Decentralized and Cooperative Control", Proceedings of the *American Control Conference*, Boston, MA, July 2004.

[15] D. Cruz, J. McClintock, B. Perteet, O. Orqueda, Y. Cao, and R. Fierro, "Decentralized Cooperative Control: A multivehicle platform for research in networked embedded systems", IEEE *Control Systems Magazine*, Vol. 27, No. 2, April 2007.

[16] Olsen, E. A., Park, C-W., and How, J. P., "3D Formation Flight Using Differential Carrier-Phase GPS Sensors", ION Navigation, Vol. 46, No. 1, 1999.

[17] Koo, T. J., *Vanderbilt Embedded Computing Platform for Autonomous Vehicles (VECPAV)*, Available online at http://www.vuse.vanderbilt.edu/ kootj/Projects/VECPAV/, July 2006.

[18] Holland, O., Woods, J., Nardi, R. D., and Clark, A., *Beyond Swarm Intelligence: The UltraSwarm*, Proceedings of the 2005 IEEE Swarm Intelligence Symposium, Pasadena, CA, June 2005.

[19] Vicon, *Vicon MX Systems*, Available online at http://www.vicon.com/products/viconmx.html, July 2006.

[20] Draganfly Innovations Inc., *Draganfly V Ti Pro Website*, Available online at http://www.rctoys.com/draganflyer5tipro.php, January 2006.

[21] Kuwata, Y., *Trajectory Planning for Unmanned Vehicles using Robust Receding Horizon Control*, Ph.D. Thesis, Massachusetts Institute of Technology, February 2007.

[22] Culligan, K., Valenti, M., Kuwata, Y., and How, J.P., "Three-dimensional flight experiments using on-line mixed-integer linear programming trajectory optimization," To appear in the Proceedings of the *American Control Conference*, New York, NY, June 2007.

[23] Valenti, M., Bethke, B., How, J.P., and Vian, J., "Embedding Health Management into Mission Tasking for UAV Teams", To appear in the Proceedings of the *American Control Conference*, New York, NY,

June 2007.

[24] Bethke, B., Valenti, M., How, J. P., and Vian, J., "Cooperative Vision Based Estimation and Tracking Using Multiple UAVs", Proceedings of the *Conference on Cooperative Control and Optimization*, Gainsville, FL, January 2007.

[25] Frank, A., Valenti, M., Levine, D., and How, J. P., "Hover, Transition, and Level Flight Control Design for a Single-Propeller Indoor Airplane", To appear in the Proceedings of the AIAA *Guidance, Navigation, and Control Conference and Exhibit*, Myrtle Beach, SC, August 2007.

[26] Valenti, M., Bethke, B., Dale, D., Frank, A., McGrew, J., Ahrens, S., How, J. P., Vian, J. "The MIT Indoor Multi-Vehicle Flight Testbed", In Proceedings of the IEEE *International Conference on Robotics and Automation*, 10-14 April, 2007, Rome, Italy.