Fourteen Years of Autonomous Rotorcraft Research at the Georgia Institute of Technology

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ABSTRACT

This paper presents a brief history and description of capabilities of the Georgia Tech Unmanned Aerial Vehicle Research Facility, while extracting and summarizing many significant and applicable results produced in the last fourteen years. Twenty-six selected publications are highlighted, which are representative of the research conducted at GT-UAVRF since 2000. The papers are divided into three groups: 1) development of a fault-tolerant adaptive flight control system, 2) development of vision-based navigation and control algorithms, and 3) special applications. For each group, the research and results are described, with references to the relevant paper(s).

INTRODUCTION

The Georgia Institute of Technology Unmanned Aerial Vehicle Research Facility (GT-UAVRF) is well known for its research in the areas of UAV guidance, navigation, and control. Since 2000, GT-UAVRF has been involved in a wide range of research activities and produced an extensive list of publications, many of which have served as inspiration and guidance for researchers around the world.

GT-UAVRF History

The development of GT-UAVRF's adaptive flight control software, the baseline of which was created 2000-2004, was enabled by several events. The GT-UAVRF was established by Drs. Anthony Calise and Daniel Schrage, whose efforts provided the theoretical and financial foundation for the lab's work. Dr. Eric Johnson was hired as the director of GT-UAVRF and received significant initial funding through a DARPA project called Software Enabled Control (SEC). The facility also acquired a Yamaha R-Max helicopter as a test platform, and the lab was staffed by a team of highly talented graduate students and research engineers.

Initial work focused on developing a high-fidelity flight simulator, called the Georgia Tech UAV Simulation Tool (GUST), as well as a baseline neural-network adaptive flight control architecture. The DARPA-funded SEC project included a number of collaborators, whose software would be tested on GT-UAVRFs R-Max, now designated as GTMax. GT-UAVRFs flight control software would then serve as the baseline controller for advanced applications from other team members. Flight testing of the GTMax and GT-UAVRFs baseline flight controller started in 2001 and lasted until the summer of 2004. The development effort benefited to a large degree from the reliability of the GTMax platform and the performance of GUST.

Subsequent work focused on the flight testing of a small ducted fan, called the Helispy, or GTSpy. A small autopilot, designated FCS20, was designed to control the vehicle. The GTSpy was successfully demonstrated in July 2004 to DARPA during the SEC final demonstration.

In 2005, GT-UAVRF began examining vision-based estimation and control. The lab was funded by an Air Force Multi-University Research Initiative (MURI), and successfully demonstrated closed-loop vision-based formation flight with two UAVs. A team of graduate students and scientists at Georgia Tech and other US universities supported the effort to develop the software. Additional research efforts in subsequent years included the examination of autonomous obstacle avoidance, automatic transition from forward flight to a hover for a fixed-wing aircraft, and indoor navigation applications, among others. The GT-UAVRF continues today as a leader in guidance, navigation, and control (GNC) research for autonomous aerial vehicles.

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TEST AIRCRAFT AND INFRASTRUCTURE

GTMax (2001 to present)

In order to achieve SEC program goals, a Yamaha RMax (Figure 1) was instrumented with custom avionics, a set of simulation tools and baseline flight control software were developed, making use of an adaptive artificial neural network (ANN) and a model-free, 17-state Extended Kalman Filter. The GTMax has been the workhorse of GT-UAVRF, offering an ideal combination of endurance, handling qualities, speed, payload, and reliability (Refs. 1–4).

The GTMax system is comprised of the following components:

- 2 Embedded PCs
- Inertial Sciences ISIS-IMU Inertial Measurement Unit
- NovAtel OEM-4 differential GPS
- Custom made ultra-sonic sonar altimeter
- Honeywell HMR-2300 3-Axis magnetometer
- Actuator control interface
- 11 Mbps Ethernet data link and an Ethernet switch
- FreeWave 900 MHz serial data link

Fig. 1. GTMax autonomous rotary-wing research platform.

GTSpy (2004-2005)

The GTSpy was a small, ducted fan vehicle based on the Helispy designed and manufactured at the time by Micro Autonomous Systems (Figure 2). It was capable of hovering and forward flight (Ref. 5). The GTSpy was instrumented with GT-UAVRFs FCS20 flight control system.

Fig. 2. GTSpy small ducted fan aircraft.

GTEdge (2005-2008)

The GTEdge, shown in Figure 3, is a modified version of a gasoline-powered, remote-controlled, 33% model of the Zivko Edge 540T, an acrobatic airplane produced by Aeroworks. The Edge was selected for its high power-to-weight ratio, providing the ability to carry moderate payloads and perform aggressive aerobatic maneuvers including hovering flight. The GTEdge avionics package is also based on the FCS20.

GTQ (2010-Present)

Motivated by the International Aerial Robotics Competition (IARC), several multi-rotor vehicles were designed and employed to develop indoor and GPS-free air navigation capabilities. The GTQ (Figure 4) offers a sophisticated and reconfigurable research platform for this effort. The GTQ's avionics package includes:

- Hokuyo URG-04LX-UG01 laser range finder
- MB1040 LV MaxSonar EZ4 sonar altimeter
- Analog Devices ADIS-16365-BMLZ Inertial Measurement Unit (including 3-axis digital gyroscope and 3-axis accelerometer)
- Two Gumstix Overo Fire single-board computers (with ARM Cortex-A8 CPU and 802.11g wireless link)

Fig. 3. GTEdge high-performance fixed-wing platform.

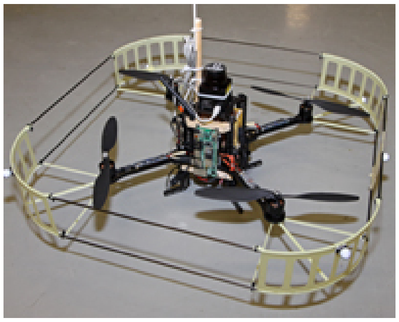

Fig. 4. GTQ indoor quadrotor platform.

Ground Control Station

GCS Computer and Software The GT-UAVRF ground control station (GCS) is normally run on a Windows or Linux-based laptop or desktop computer. It provides the user with the primary interface to the autopilot and aircraft in all possible simulation and flight test configurations (see Figure 5). In addition to the user interface, the GCS software hosts the datalink to the onboard software and the interface with differential GPS if in use.

The GCS allows user interaction with the system via a console, a variable browser, and a scene visualization window, which allows a great deal of flexibility to the user to both monitor and control the aircraft. Because of the flexibility of the GCS and datalink software, the same ground station software is used for all vehicles flown in GT-UAVRF research programs.

Communication Equipment The GCS computer is connected to the aircraft via a hardware package consisting of a network switch, wireless bridge, wireless serial transceiver, and a combination of directional and omnidirectional antennas. The suite also includes the base station for high-accuracy differential GPS.

Support Equipment GT-UAVRFs ground support equipment has been crucial to supporting flight test activities. The ground support equipment consists of a truck equipped with auxiliary power generation, tool and part storage, backup uninterruptable power supply, climate controlled environment, operator workstation, and observation window. The truck doubles as the transport mechanism of the aircraft, and gives GT-UAVRF flexibility in flight test locations.

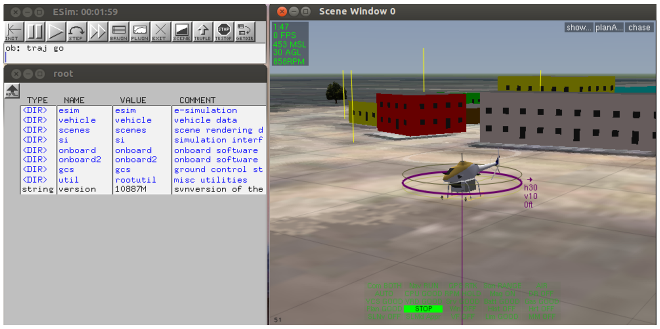

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Fig. 5. The Ground Control Station with console, variable browser, and scene window.

Fig. 6. UAVRF ground support equipment.

RESEARCH

The hardware and software systems described above have been the foundation for the exploration of a broad range of

GNC topics. Select results are summarized in this section from each of the major areas of investigation.

Adaptive and Fault-Tolerant Control

Adaptive and fault-tolerant control was and continues to be a core research area for GT-UAVRF. The GTMax, in much of the early research, served as the proof-of-concept for the theoretical ideas developed and published, though the adaptation has been successfully applied to several other vehicles.

Neural Network Adaptive Control Among the earliest research published featuring GT-UAVRF research aircraft, (Ref. 6) stands out for presenting the foundation of the baseline autopilot. For autonomous helicopter flight, it is common to separate the flight control problem into an innerloop that controls attitude and an outerloop that controls the trajectory of the helicopter. However, since the attitude and translational dynamics are coupled, adaptive controllers on the two loops attempt to adapt to each other, resulting in poor overall performance. A pseudo control hedging (PCH) method was introduced that allows for adaptation in the outerloop while preventing adaptation to the innerloop dynamics (Ref. 6). Additionally, hedging was used in the innerloop to avoid incorrect adaptation while at control limits (Figure 7). This approach mitigated inner/outer loop interaction problems and allowed increased bandwidth in the outerloop, improving tracking performance. Work published in (Ref. 7) refined the application of PCH and explored the ability of the controller to tightly track a specified trajectory in aggressive maneuvering. Finally, the neural network adaptation in the controller successfully compensated for faults and damage in multiple aircraft (Ref. 8).

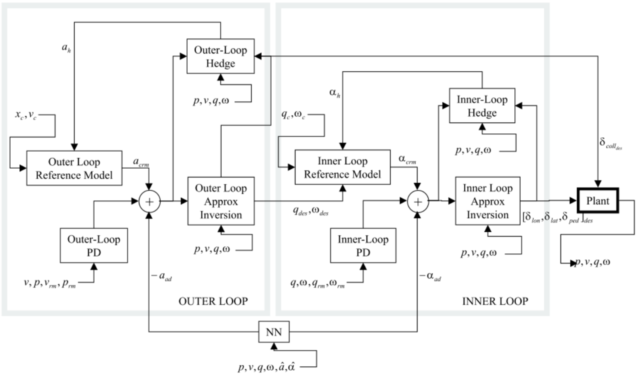

Fig. 7. Detailed inner- and outer-loop controller architecture for an autonomous helicopter, from (Ref. 6).

The GTSpy flight test effort (2004 - 2005) triggered several important improvements to the GT-UAVRF flight controller. Ref. (Ref. 5) describes the development of a simulation model, application of the GTMax's dynamic inversion controller with neural network adaptation, and flight test results. This paper also reported a flight test experiment in which the GTSpy was launched in the air from the GTMax, autonomously attaining a stable hover (Figures 8 and 9). This may have been the first successful in-air launch of one hovering vehicle from another.

Fig. 8. First air launch of a hovering aircraft.

Fig. 9. The GTMax with GTSpy prior to air launch.

The baseline controller was also successfully adapted to fixed-wing aircraft. Early fixed-wing work focused on finding an adaptive controller that could adequately control an airplane in very low-speed flight, high-speed flight, and transitions in between. The inversion controller described above was applied to the GTEdge, an eight-foot wingspan, fixed-wing unmanned aircraft system which had been fully instrumented for autonomous flight. Data presented in (Ref. 9) describes actual flight-test experiments in which the airplane autonomously transitions from high-speed, steady-level flight into a hovering condition and then back again.

Georgia Tech UAV Simulation Tool Early in the GTMax system design process, a number of top-level simulation capability requirements were identified to support the development and operation of experimental UAVs. The product that resulted from these requirements is known as the Georgia Tech UAV Simulation Tool, or GUST (Ref. 10).

In order to test each element of the system, separately, the simulation was developed to accommodate multiple configurations, run actual flight control code and include models of the sensors, actuators, aircraft dynamics, wireless datalinks, and terrain down to the level of binary serial data with time delays. As a result, it is possible to use the simulator in a vast array of configurations and mission scenarios, from fully simulated flight taking place in a single executable on a single computer, to injecting simulated sensor data to the real aircraft in flight, to playing back recorded flight data on a ground station. The incremental nature of these simulations enable the detection of potentially critical failures before the aircraft ever leaves the laboratory.

FCS20 Compact Navigation and Control System The FCS20 miniature flight control system was designed in 2004 to enable autonomous operation of smaller vehicles at GT-UAVRF using the same flight control software as the GTMax helicopter (Ref. 11). The initial motivation for the design of the FCS20 was the need for a flight control system for the GTSpy, the small ducted fan, which was part of the DARPA SEC project (2000—2004). Later, the FCS20 became the default flight control system for all of the smaller research vehicles used in the GT-UAVRF and enabled many of the technical demonstrations presented here. The FCS20 is currently in production under a license to Adaptive Flight, Inc. and primarily used to control their series of Hornet$^{\text{TM}}$ unmanned helicopters.

The FCS20 is a fully integrated Flight Control System, which consists of a processor board and a sensor board. The processor board contains all circuits required for fast and efficient signal processing and the sensor board contains all navigation sensors, power supply circuits and system interface circuits. The FCS20 offer the following unique features:

- Powerful Digital Signal Processor (DSP) enables execution of demanding flight control applications
- Advanced Field Programmable Gate Array (FPGA) offer flexible interface options (100+ General Purpose Input / Output pins) and contribute significantly to the FCS20s overall processing capabilities.
- Ethernet Port, SPI, I2C, RS232 (multiple)
- Real-time Stability Augmentation System (SAS) for helicopters
- Credit-card size

Computer Vision

Another core research area at GT-UAVRF has been the application of computer vision to enhance aircraft state estimation as well as awareness and navigation capabilities relative to obstacles and other aircraft (Refs. 4, 12–17).

Vision-Aided Inertial Navigation Initial efforts to develop vision-based navigation capabilities at GT-UAVRF involved the development of important tools and methods for the visual detection of pre-defined targets, the ability to determine own position relative to such targets and finally the ability to navigate relative to such targets. In (Ref. 13) a helicopter equipped with a fixed monocular camera and an image processor is used to detect a window in a building and fly toward it. In Ref (Ref. 14), a small fixed-wing glider uses an off-board image processor to guide itself toward a square target. Efficient methods for detection of known targets were developed and demonstrated in flight. Extended Kalman Filters were employed to fuse information from the image processor about the relative position of the target, with data from the vehicles inertial sensors, in order to correct for drift in the navigation solution.

Later work expanded the capability of the vision algorithms by implementing a database of feature locations which were estimated simultaneously with the vehicle state. This system enabled bounding of the horizontal position of the vehicle in the absence of GPS and predefined features. Flight tests demonstrated the system during 16 minutes of continuous flight, and during landing on an unprepared site. The system was successfully implemented on both the GTMax and a smaller, indoor aircraft (Ref. (Ref. 17)). Figure 11 shows the results of one 8 minute portion of a flight with no horizontal GPS. The oval trajectory was flown first at 6.1 m/s and then at again at 9.1 m/s. The final position error was less than 5 m.

Air-to-Air Tracking and Formation Flight Computer vision has proved useful in providing information about other aircraft for use in formation flight or air-to-air tracking. A 2007 paper (Ref. 15) described two vision-based techniques for the navigation of an aircraft relative to an airborne target using only information from a single camera fixed to the aircraft. One method used the controller to position the aircraft for maximum accuracy in range estimation, while the other performed more rigorous image processing to achieve similar performance (see Figure 10). Simulation results indicated that both methods yield range estimates of comparable accuracy while placing different demands on the aircraft and its systems.

Obstacle Avoidance and Terrain Mapping One of the most promising applications of computer vision is use for identifying terrain for collision avoidance purposes. Cameras offer an inexpensive alternative to other ranging devices, such as lasers or radar. A 2005 paper, (Ref. 12), described a 3D obstacle modeling system which used a 2D vision sensor to track obstacle edges. The approach detected edges as line segments using an image segmentation technique, then modeled them in a 3D space from the measured line segments using known camera motions. Simulation results showed that simple structures could be accurately modeled by such a line-based estimator, and applied them to a 3D terrain mapping problem. More recent work has used feature point detection and estimation with inverse depth parameterization. The converged point estimates were used to update a terrain map kept for obstacle avoidance purposes.

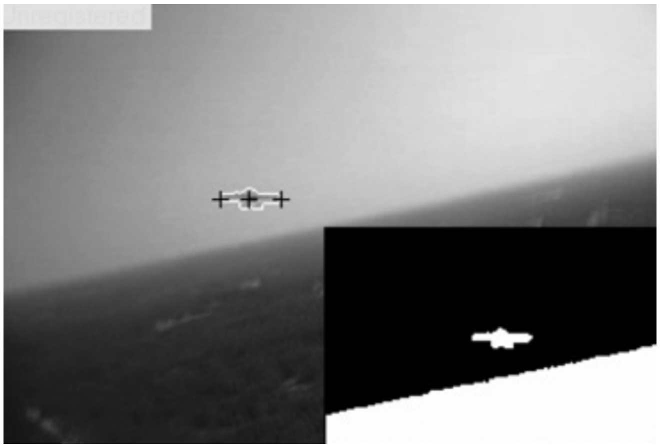

Fig. 10. Example image used in tracking. Note the crosshairs indicating both position and attitude. From (Ref. 15).

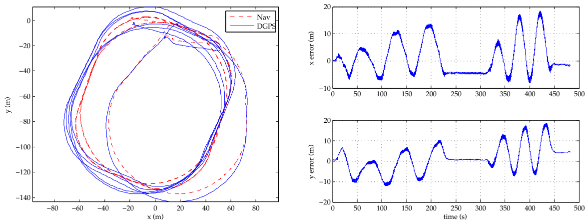

Fig. 11. Example trajectory tracking performance of vision-aided navigation over an 8 minute portion of a flight. The blue line is the differential GPS output and the red line is the vision-aided navigation solution.

Special Applications

Slung-Load One of the more recent lines of investigation has involved the ability of autonomous helicopters to carry under-slung loads. This is a very difficult problem, as a slung load adds several degrees of freedom to the already complex helicopter dynamics. Two publications from GT-UAVRF so far have attempted to tackle this problem. The first, (Ref. 18), used vision-based techniques to estimate the state of the load, essential to effectively control and stabilize it. The second, (Ref. 19), studied the use of a pre-filtering technique called input shaping to limit load swing (see Figure 12).

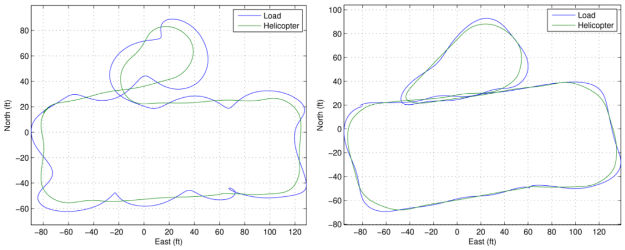

Fig. 12. Simulation result showing slung-load flight with and without input shaping, from (Ref. 19).

Nap-of-the-Earth Flight As UAVs expand into wider varieties of applications, the ability to maneuver autonomously in unknown and hazardous environments is increasingly vital to their effectiveness. Helicopters, in particular, have capabilities well-suited to flight in low-altitude, obstacle-rich environments. Techniques to realize those capabilities have been an active area of research in GT-UAVRF. Work published in (Ref. 20) and in (Refs. 21, 22) demonstrated several obstacle mapping and avoidance techniques. More recent work has focused on aircraft sharing terrain data for collaborative obstacle avoidance (Ref. 23).

Indoor Navigation Indoor flight presents a special set of circumstances from a GNC standpoint. First, the lack of GPS signals makes accurate position estimation difficult. Second, while outdoor vehicles can climb to avoid obstacles, the indoor vehicle is typically surrounded by obstacles. Research at GT-UAVRF has tackled both problems, with demonstration of the developed technology in the International Aerial Robotics Competition (IARC).

Research involving the GTQ platform uses a streamlined simultaneous localization and mapping (SLAM) algorithm to provide a position and heading estimate, which, when combined with other sensor data, forms an inertial navigation solution. Additionally, this data is used to search indoor environments by developing a map and selecting frontiers for exploration. The avionics design and the GNC algorithms have been validated through flight tests and competition (Ref. 24).

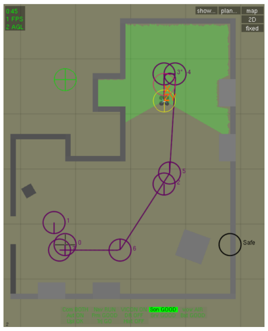

Fig. 13. GTQ mapping a simulated environment, from (Ref. 24).

International Aerial Robotics Competition The GT-UAVRF also serves as the supporting laboratory for the Georgia Tech Aerial Robotics Team (GTAR). GTAR is a student organization which participates in a variety of aerial robotics competitions, which have had an important impact on the development of key capabilities of GT-UAVRF. Design of systems for particular competitions has benefited from and contributed to ongoing research projects; in particular vision-aided navigation, slung-load operations, GPS-denied navigation, and complex mission planning. GTAR has regularly participated in the AUVSI-sponsored International Aerial Robotics Competition (IARC) since 2003, finishing as one of the top teams each year (Ref. 25).

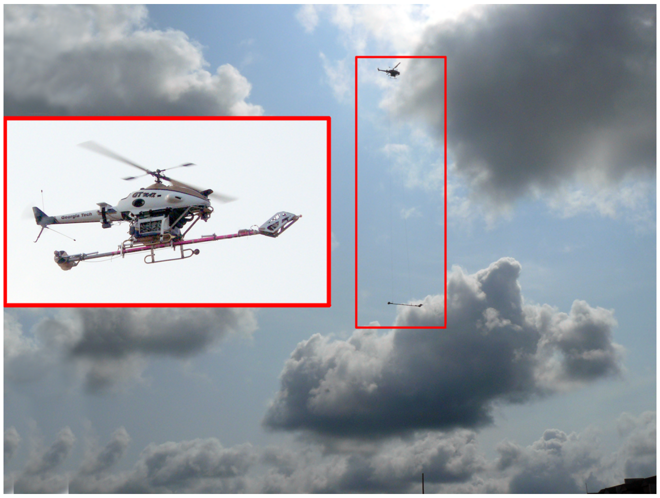

Fig. 14. The 2008 GTAR entry for the International Aerial Robotics Competition. The system was designed to deploy a mobile robot into a building. The GTAR team was awarded top prize.

CONCLUSIONS

The Georgia Tech UAV Research Facility continues to be a leader in guidance, navigation, and control research for unmanned aerial systems. The group has made significant advances in adaptive and fault-tolerant control, vision-based estimation, and guidance for rotorcraft-specific tasks. The aircraft, software, and ground support equipment developed within GT-UAVRF have enabled these several significant contributions to the field, and promise to continue to do so for many years.

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