Software Enabled Control
for
Innovative Control Technologies for Autonomous Highly Agile and Extreme-Performance Aerial Vehicles

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Status Report
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Project Objectives:

The objective of this project is to develop innovative software-enabled control (SEC) methods and Open Control Platform (OCP) support for complex dynamic systems with an application focus on intelligent Uninhabited Aerial Vehicles (UAVs). UAVs that are capable of extreme performance under complex and changing mission scenarios require such intelligent attributes as fault-tolerance, adaptation and learning. Software architectures needed to support controls technology with these features must be capable of plug-and-play of control algorithms, rapid on-line algorithm reconfiguration, and distributed real-time computing. The specific objectives of the project are to develop innovative mid-level hybrid control algorithms for mode transitioning and fault accommodation that are customizable and reconfigurable during flight, and to develop an Open Control Platform (OCP) to support this new controls technology with specific emphasis on providing generic mechanisms for integrating and dynamically reconfiguring these mid-level hybrid control algorithms.

Approach:

The approach is to use a hierarchical control architecture where mission planning and situation awareness are at the highest level, the flight control (including stability control augmentation) is at the lowest level, and a mid-level controller coordinates the transitions between modes and provides fault-tolerant reconfigurable control. The flexible integration of these dynamic control system components and their reconfiguration and customization during flight are enabled by an underlying Open Control Platform. These innovative controls and software technologies will be demonstrated on a Vertical Takeoff and Landing (VTOL) UAV, the Yamaha R-50/RMAX Remotely Piloted Helicopter (now named GTMax), using hardware-in-the-loop and integrated distributed simulation, along with selective flight test demonstration.

Status of the Project:

The OCP support and the SEC algorithms being developed at Georgia Tech have focused on the mid-level control of an unmanned air vehicle (UAV) conducting extreme performance maneuvers. This is particularly challenging for on-line customization and provides a set of requirements for both the OCP technology and the SEC algorithms. A continuing effort is to optimize the mode transitioning and fault tolerant control algorithms already developed (see publication list submitted to sponsor) and to incorporate them in the OCP architecture and to implement them in the hardware-in-the-loop demonstration. Flight tests are being conducted and additional ones are planned for these mid-level control strategies and for limit detection and avoidance for the next quarter. These will use the Hybrid Controls API being developed at Georgia Tech.

There are three main tasks listed in the revised statement of work submitted February 2001:

- Task I: Hybrid Controls API for OCP
- Task II: Demonstration of OCP integrated control algorithms for achieving High Confidence Performance in Unmanned Aerial Vehicles.
- Task III: Transfer of Technology

The recent accomplishments for each task are given below. The project is on schedule for each of the subtasks.

Task I: Hybrid Controls API for OCP

Transition Management: The goal of the hybrid controls API is to provide transition management support for flexibly transitioning between modes. Most theoretical hybrid control algorithms assume a discrete switch between controllers. However, jumps in the controller can cause undesired transients. Most practitioners introduce a method to smooth the transitions between modes; the most common being gain scheduling. We are building the transition manager to provide common patterns for such transitions. In particular, we have worked with Vanderbilt and University of Budapest to identify the following common strategies:

- Discrete switch
- Blending of the outputs
- Gain scheduling
- Initialization (including state preserving, output preserving)
- Transient Compensation

Except for the discrete switch, the transition strategies require that the corresponding software components cannot be simply turned on and off when a transition is needed. There needs to be a period where both components are active.

Recent results: The Hybrid Controls API was provided to Boeing for incorporation into the next release of the OCP. This includes transition management mechanisms that are built on their Transition Service and a set of examples that demonstrate basic transition management strategies. A paper will appear in the *IEEE Control Systems Magazine* (February 2003) on generic mechanisms for transition management. We are planning to use the Hybrid Controls API to facilitate control algorithms that will be demonstrated in the mid-term exam.

We also pre-released the Hybrid Controls API to Vanderbilt/ISIS and they provided us with their FACT-OCP demonstration system. This is moving us toward unified code generation capabilities for reconfigurable hybrid controllers.

Validation: As a critical step toward mid-term and final exam demonstrations, we defined interfaces for the primary mid-level algorithms (e.g., trajectory generation, limit detection and avoidance) and how they communicate with the low-level flight controller over a data link between the primary flight computer and the secondary (mid-level controls) flight computer. These were tested successfully in the November flight test.

Although we had planned to use VxWorks as the real-time operating system underlying the OCP on the secondary flight computer, for several reasons, we decided to switch to a QNX-based environment. The foremost reason was that since QNX is in the public domain and is already being used by many of the SEC teams, it will be easier for our partners in the university-led demonstration to incorporate their software into our demonstration platform. The other technical reasons were that 1) the primary flight computer is running QNX, so choosing a single operating system simplifies our design and the communication between the primary and secondary computers (and may make it easier to redistribute functionality in the future between the two computers), and 2) for some of our algorithms, we were having severe timing difficulties due to incompatibilites with our Ethernet chip set and the version of VxWorks we had available.

We have constructed example scenarios to validate the transition management and dynamic reconfiguration strategies in an OCP flight test implementation (in addition to simulation). We have an adaptive mode transitioning algorithm that is running on the OCP into which we are incorporating transition management mechanisms (currently, the management is hard-wired into the C++ code and is difficult to validate and change). We are also working out the details of how the transition management and dynamic reconfiguration capabilities of the OCP will be used in a fault detection and recovery scenario and in a multiple limit detection and avoidance scheme.

Control Algorithms: Several mid-level control methods have already been developed under this program that enable a UAV to increase its envelope of performance. These include a mode transitioning methodology and a limit detection and avoidance methodology (that adjusts the actuator commands so that the vehicle is not commanded to exceed its performance/structural limits), and a fault tolerant control methodology. These methods are generic in nature and can be applied to many different systems. Implementation details are discussed below.

Limit Detection and Avoidance: During this reporting period, the adaptive limit detection and avoidance algorithms have been integrated with the low level flight controller of the Rmax helicopter and software-in-the-loop (SITL) simulation evaluations have been carried out. The main rotor stall avoidance in terms of the main rotor equivalent retreating indicated tip speed (ERITS) limit is used as an example. An ERITS factor lower limit of 300 ft/sec usually corresponds to rotor blade stall. ERITS factor is a function of rotor rpm, calibrated airspeed and the load factor. The sensor measurement of the accelerations and control deflections are filtered using a first-order low pass filter with a cut off frequency of 2Hz. The load factor is then computed using the filtered values of the vehicle accelerations. The calibrated airspeed is computed using the measured velocity along the three axes.

Mode Transition Control: During this reporting period, the following tasks were completed.

The Adaptive Mode Transition Control algorithms have been migrated to version 2.1 of the OCP and tested in software in the loop simulation. Part of the architecture that accompanies those algorithms, including mission and trajectory planning components, was tested successfully in flight test and demonstrated at the last PI meeting. Current effort is focused in a flight test of the whole architecture and use of the Hybrid Controls API through the OCP to facilitate the implementation of the algorithms.

Publications
Gutierrez, L. B., Vachtsevanos, G., and Heck, B., "A Hierarchical/Intelligent Control Architecture for Unmanned Aerial Vehicles," in Proceedings of the 21st Digital Avionics Systems Conference, pp. 8.B.4-1/8.b.3-10, Irvine, CA, October 27-31 2002.

Gutierrez, L. B., Vachtsevanos, G., and Heck, B., "An Approach to the Adaptive Mode Transition Control of Unmanned Aerial Vehicles," submitted to 2003 American Control Conference.

Fault Tolerant Control: The hierarchical fault tolerant control architecture consists of a high level (FDI and situation awareness), a mid level (control algorithms), and a low level (subsystems and their interconnections). The mid level algorithms control the set points of the individual subsystems, the interconnections between subsystems (to the extent possible), and the subsystem controller gains.

The following progress has been made on the fault tolerant control algorithms. The neural network fault detection and identification (FDI) routine has been tested in software-in-the-loop simulation using the OCP. Work is currently being directed to compiling the code for the onboard computer and flight tests. Also, with the recent addition of an rpm sensor on the helicopter, the rpm controller algorithm is being transferred to the OCP for software-in-the-loop testing of the fault tolerant configuration architecture, simulating a failure of the main rotor collective.

New proofs for the stability of the fault tolerant control routines have also been advanced. For these proofs, a 'trim state' (or state where the dynamic equations are equal to zero) for the aggregate large scale system is first found using an optimization routine. This routine optimizes the search based on a weighted average of the deviation from the nominal state and previous state and setpoints. A 'transformed system' is then determined by subtracting out the trim state equations from the full dynamic equations. The stability of the system is then addressed by finding an update law for the dynamics of the interconnection structure and setpoints which drives the dynamics of the transformed system to the origin (an idea borrowed from robust adaptive control algorithms).

Task II: Demonstration of OCP integrated control algorithms for achieving High Confidence Performance in Unmanned Aerial Vehicles.

The Georgia Institute of Technology hosted on November 6-8, 2002, the semi-annual Principal Investigators' meeting of the DARPA Software Enabled Control (SEC) program. Industry and university researchers are developing for DARPA innovative control technologies and an open systems software architecture called Open Control Platform (OCP) with application to autonomous unmanned vehicles. The principle objective of the program is to develop software enabled control technologies that will enable autonomous vehicles to achieve reliable and robust performance in the execution of surveillance, reconnaissance, targeting, and strike missions, including operations in an urban environment. Georgia Tech has been developing, in collaboration with other program participants, control algorithms for a VTOL UAV, supporting their implementation on the OCP, and developing a research UAV to support flight test verification of these technologies.

On November 8, approximately 50 participants in the SEC program took time during this meeting to witness flight operations of the Georgia Tech Yamaha R-Max research UAV (GTMax), at its McDonough, Georgia flight test facility. Attendees included the DARPA SEC Program Manager and the Georgia Tech Contract Monitor from AFRL. Beyond Georgia Tech, the program collaborators include: Boeing, CalTech, Cornell University, Draper Laboratory, Honeywell Laboratories, MIT, UC Berkeley, Stanford University, STA, Inc., Northrop Grumman, CACI, University of Minnesota, University of Colorado, SoHaR, Inc., Oregon Graduate Institute, SSCI, Xerox PARC, Veridian Flight Research, Vanderbilt University, SRI International, and Rockwell Collins; many of whom were in attendance.

The GTMax did all of its own flying utilizing its baseline guidance, navigation, and flight control hardware/software, including takeoffs/landings, setting up for flight test data collection runs, and aggressive maneuvers (a safety pilot was also on hand to take over in case there was any problem).

Maneuvers performed by the system included step responses of the position control, level flight and banked turns up to 50 ft/sec (forward and backward), an aggressive 180 degree turn requiring only about 60 ft, pirouettes, simulated flight in an urban environment, flight testing of a limit detection and avoidance algorithm, flight testing of a trajectory generation algorithm, as well as all takeoffs, departures, approaches, and landings. The safety pilot was only required to add fuel, start/shutdown the engine, and be prepared to take over if in case it had become necessary.


The GTMax system includes the Yamaha R-Max helicopter platform, onboard sensing, processing, and communication hardware, and a ground control station. The airborne elements include differential GPS, an inertial measurement unit, sonar altimetry, two general-purpose computers, a wireless serial link, and a wireless Ethernet link. The ground control station components include a reference GPS, two laptop computers, and the data links. There is also a safety pilot backup on a third radio link. The vehicle can be safely recovered as long as one of the three data links is operational. A remote display of the ground control station was also provided for those witnessing the flight operations, which includes a display of the current vehicle trajectory command, vehicle position estimate, and component status.

Four important SEC technologies were included in flight operations. These include the OCP software, adaptive flight control for aggressive maneuvering, limit detection and avoidance, and trajectory generation. Plans for future flight operations under the SEC program include: Hybrid controls API, environment-informed sensing and control, statistical verification of computational performance, autonomous aggressive maneuver trajectory generation, mode switching model predictive control, and fault detection/isolation/recovery. In February 2002 Georgia Tech was designated by DARPA as the SEC University Experiments lead with the GTMax chosen as the testbed for these experiments that would lead to and be incorporated in the SEC Mid Term and Final experiments. To ensure relevance of the SEC technologies, a realistic mission scenario has been drafted, relevant to current concepts of operations envisioned by DARPA for urban warfare. For instance, integrating the autonomous flight capability of UAVs with sensing, identification and engagement of critical targets has become a focus for the Information Exploitation Office. The six steps in the mission scenario are:

1. Takeoff and fly autonomously to the area of interest, i.e. an urban setting.
2. Identify a particular structure and openings
3. Send possibly an OAV through a (closed) window into the building

4. Execute surveillance and detect a target
5. Strike target
6. Complete the mission in less than 15 minutes

After the flight operations, time was taken for the SEC participants to examine the GTMax hardware up close and to ask questions of its developers and current users. This was particularly useful for those currently working with Georgia Tech to collaborate on the SEC program university-led final flight experiments. It gave them a genuine feel for what the vehicle is like to work with, and the potential to use this system to test and demonstrate their technologies.

These efforts are an important element of the SEC program, providing flight test verification of SEC technologies: improved autonomy, increased reliability, greater flight control system performance, and new operations of UAVs in an urban environment. It also provides a logical transition path to operational VTOL vehicles. To this end, Georgia Tech is exploring with DARPA the feasibility of transitioning SEC technologies to more relevant vehicles.

Georgia Tech SEC web page: **http://controls.ae.gatech.edu/sec**
Video clips from November 8, 2002 flights: **http://controls.ae.gatech.edu/uavrf/videos**

Task III: Transfer of Technology

Georgia Tech is working closely with several SEC contractors: Boeing, UC Berkeley Vanderbilt/Budapest, and others. In particular, Boeing provided support for the flight controls demonstration and, in turn, Georgia Tech is providing feedback and requirements for the OCP. Georgia Tech is also relying on Boeing's Transition Service for the Hybrid Controls API, while Boeing will incorporate the Transition Manager into the OCP. Vanderbilt/Budapest has helped define transition management strategies for the Hybrid Controls API. The modeling for the transition manager is being done using Ptolemy II with help from UC Berkeley. The UC Berkeley group has extended Ptolemy II to include the capability needed for the blending function. This extension will be available in the next release of the software.