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System Integration and Operation of a Research Unmanned Aerial Vehicle

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The use of flight simulation tools to reduce the schedule, risk, and required amount of flight testing for complex aerospace systems is a well-recognized benefit of these approaches. However, some special challenges arise when one attempts to obtain these benefits for the development and operation of a research unmanned aerial vehicle (UAV) system. Research UAV systems are characterized by the need for continual checkout of experimental software and hardware. Also, flight testing can be further leveraged by complementing experimental results with flight-test validated simulation results for the same vehicle system. In this paper, flight simulation architectures for system design, integration, and operation of an experimental helicopter-based UAV are described. The chosen helicopter-based UAV platform (a Yamaha R-Max) is well instrumented: differential GPS, an inertial measurement unit, sonar altimetry, and a three-axis magnetometer. One or two general-purpose flight processors can be utilized. Research flight test results obtained to date, including those completed in conjunction with the DARPA Software Enabled Control program, are summarized.

I. Introduction

Recently, the effectiveness of commercial electronics and the maturation of unmanned aerial vehicle (UAV) technologies are such that sophisticated flight test research can be done safely on a relatively small budget, even at the university level. The fact that a pilot is not put at risk and highly capable computers and sensors are available at lower cost makes things much easier. However, the sophistication necessary to integrate hardware and software and then operate the system to achieve desired research objectives remains.

The experience at the Georgia Institute of Technology in this area goes back to initiation of the Association for Unmanned Vehicle Systems, International (AUVSI) International Aerial Robotics Competition in 1991 (Ref. 1). This was followed by the U.S. Army Autonomous Scout Rotorcraft Testbed (ASRT) project from 1994–1997. In 1997, Georgia Tech obtained two Yamaha R-50 remotely piloted helicopters (RPH) for use in flight controls research under the Army/NASA sponsored Center of Excellence in Rotorcraft Technology (CERT) program, and represented a further shift to more capable dedicated research vehicles. Flight control technologies, such as neural network adaptive flight control, tested on these RPHs have gone on to flight tests on the X-36 and JDAM programs as well as to NASA studies.[2-5]

Other researchers have also had success utilizing Yamaha helicopters, including those at Carnegie Mellon University, NASA Ames Research Center, and UC Berkeley.[6-9] There have also been a number of efforts with smaller helicopters,[10,11] and fixed wing aircraft. NASA has also been operating other research UAVs, including the previously mentioned X-36 program. The same is true of other government laboratories, such as the Air Force Research Laboratory and the Naval Research Laboratory.

Since 1998, Georgia Tech has been a part of the DARPA Software Enabled Control (SEC) program.[12] In conjunction with these efforts, a Yamaha R-Max RPH, with twice the payload of the R-50 was acquired. Subsequently, an open system UAV testbed has been developed based on this platform. This research UAV is

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Fig. 1 GTMax research UAV.

referred to as the GTMax (Fig. 1) and includes four major elements: the basic Yamaha R-Max RPH; a modular avionics system; baseline software including middleware, guidance, navigation, control, communications, and operator interface components; and a set of simulation tools. In 2002 Georgia Tech was chosen to be the SEC rotary-wing experiments lead, which includes working with other SEC technology developers in integrating and testing their technologies on the GTMax system. An integrated simulation and flight-testing approach has been developed to support these activities. It is a process that includes Software–In-The-Loop (SITL) and Hardware-In-The-Loop (HITL) simulation as well as flight-testing. An SEC benchmark flight test was completed in May 2002 and a series of planned mid-term and final experiments will be conducted over the next 18 months.

This paper describes the development of the GTMax research UAV system, including related simulation tools, and the system integration and operation process. The GTMax system will first be described in some detail. Then, the simulation tools and processes developed to support its development and research operation will be described. Following this, significant flight test results over approximately 100 flights and conclusions are summarized.

II. Research UAV System Description

As stated previously, the GTMax research UAV consists of four major elements: the basic Yamaha R-Max airframe, a modular avionics system, baseline software, and a set of simulation tools.

A. Airframe

The GTMax utilizes the Yamaha R-Max industrial helicopter airframe, which has the following characteristics:

- Rotor diameter: 10.2 feet; Length: 11.9 feet (including rotor)
- Engine: gasoline, 2 cylinder, water cooled, 246cc, 21 horsepower
- Max weight: 205 pounds; Payload including avionics: >66 pounds
- Endurance of approximately 60 min (hover)
- Generator, battery, and electric starter
- Yamaha Attitude Control System (YACS)

B. Baseline Hardware

The hardware components that make up the baseline flight avionics include general purpose processing capabilities and sensing, and add approximately 35 lbs to the basic airframe, leading to a total weight of approximately 157 lbs. Research objectives can dictate additional equipment beyond this baseline. The digital interface to the vehicle is via a modified Yamaha Attitude Control System (YACS) interface that allows raw servo commands to be given without modification by this stability augmentation system. The YACS also has other sensor

Fig. 2 Vibration isolated avionics module rack, from left to right: data link module, GPS module, computer module #1 (flight computer), and computer module #2 (auxiliary).

outputs. The current baseline research avionics configuration includes 266 MHz Pentium II Embedded PC, 500 Mb Flash Drive, 850 MHz Pentium III Embedded PC, 2 Gb Flash Drive, Inertial Science ISIS-IMU Inertial Measurement Unit, NovAtel OEM-4, differential GPS, Honeywell HMR-2300, 3-Axis magnetometer, Custom made ultra-sonic sonar altimeter, Custom made optical RPM sensor, Vehicle telemetry (RPM, Voltage, Remote Pilot Inputs, low fuel warning) from YACS, Actuator control interface to YACS, 11 Mbps Ethernet data link and an Ethernet switch, FreeWave 900MHz spread spectrum serial data link, and Axis 2130R pat, tilt, and zoom network camera.

These components have been packaged into exchangeable modules: two computer modules, the GPS module, the data link module (wireless Ethernet, wireless serial, Ethernet switch), and the IMU module. These modules are placed in a vibration-isolated rack below the main body of the helicopter, shown in Fig. 2. Each module has its own self-contained power regulation, air-cooling, and Electro-Magnetic Interference (EMI) shielding. There is also a sonar/magnetometer assembly at the tail, a power distribution system including circuit breakers near the module rack, and mounting points for camera systems and other components under the nose. The power distribution system utilizes the onboard generator, which outputs 12V DC. It includes a hot-swappable connection to use external power. Each component has a dedicated individual circuit breaker.

Wiring external to the modules consists of RS-232 Serial, Ethernet, and 12V DC only. Wiring is routed to one side of the module rack. The other side is kept free and available for temporary hookups (e.g. Ethernet), status LEDs, and switches. The complete wiring diagram is shown in Fig. 3, including a typical configuration of RS-232, Ethernet, and power wiring. Note the compartmentalization in modules and the interface to the YACS via multiple serial lines.

C. Baseline Software

The operating systems utilized for typical onboard, flight, software are VxWorks, QNX, Linux, or a combination. Operating system independence is maintained to maximize the ability to support varied research programs. The operating system independence is accomplished by extensive use of ANSI C/C++ (and the OpenGL API for graphics used in simulations and graphical user interfaces). No special compilers are required. Normally Microsoft“ Visual Studio is used for Windows and the GNU c-compiler is used for Linux and QNX.

The onboard software runs on the two onboard computers, referred to as the primary flight computer and the secondary computer. The Ground Control Station (GCS) software runs on the ground, normally on one or more laptop computers, and allows system operators to interact with the onboard systems. Simulation-specific software refers to any software that is not used in the flight configuration. All of the aforementioned software is included in the GCS or simulation-tool builds. Typically only the onboard software is included in a primary flight computer or secondary computer build in addition to any test-specific software.

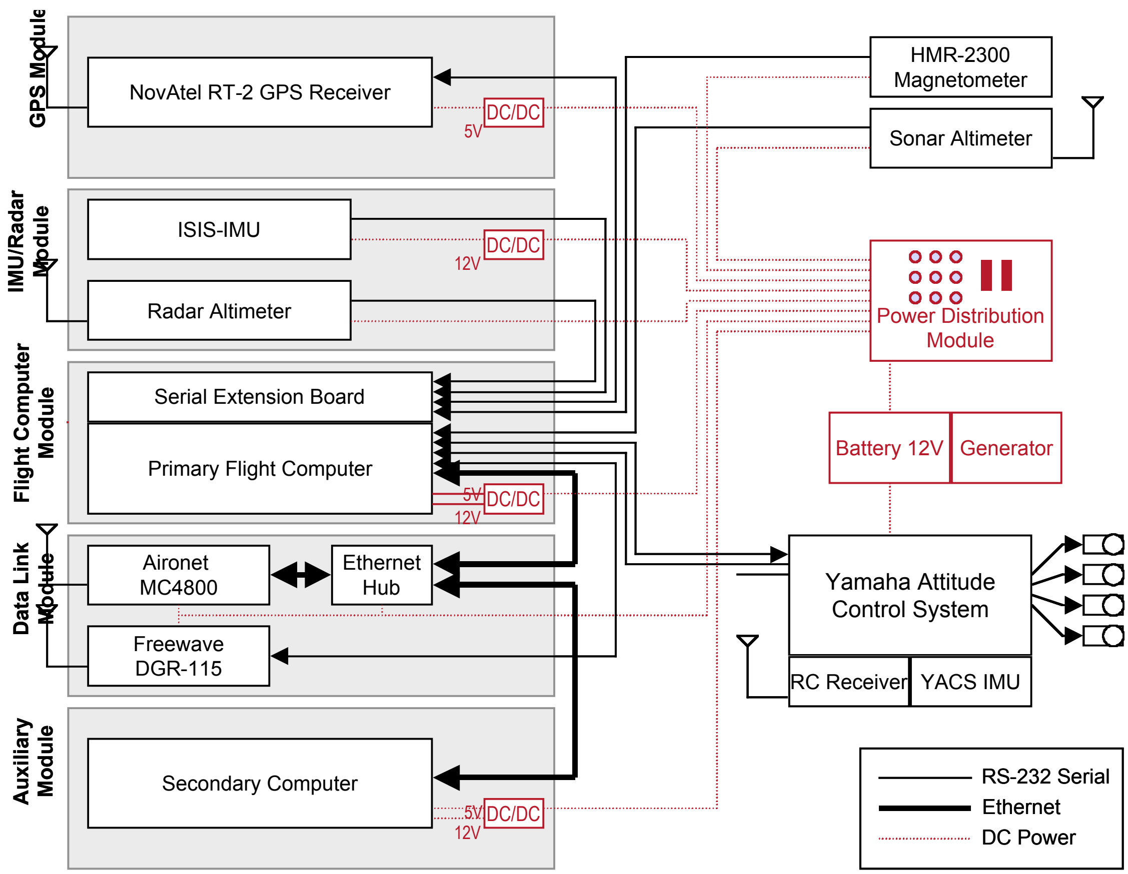

Fig. 3 GTMax wiring diagram, including separation into modules, each with their own power regulation, air-cooling, and EMI shielding

The baseline navigation system running on the primary flight computer is a 17 state extended Kalman filter. The states include vehicle position, velocity, attitude (quaternion), accelerometer biases, gyro biases, and terrain height error. The system is all-attitude capable and updates at 100 Hz (Ref. 13). The baseline flight controller is an adaptive neural network trajectory following controller with 18 neural network inputs, 5 hidden layer neurons, and 7 outputs for each of the 7 degrees-of-freedom.[14] These seven degrees-of-freedom include the usual six rigid-body degrees-of-freedom plus a degree-of-freedom for rotor RPM. The controller can also be configured as a more conventional dynamics-inverting controller.

The baseline flight controller and navigation system, which coupled with the simple baseline trajectory generator, is capable of automatic takeoff, landing, hover, flight up to the maximum attainable by the helicopter (around 85 ft/s) and aggressive maneuvering, discussed further in the results section later.

Generic and highly-capable data communication software has been developed to support a large number of potential flight and simulator test configurations. First, these routines supports serial data reading and writing as necessary for the commercial off the shelf (COTS) sensors and other custom components used. These same routines can also be used to reroute any data through Ethernet or as memory within a single executable. These data routings can be modified in real-time, by software switch. It should be noted that almost all operating system specific software is limited to these routines. These data communication routines are used to interface with all sensors, the wireless serial data link, and to repeat all wireless serial data over the wireless Ethernet, for redundancy. Also, any data received over a link can be stored to a binary file. This recorded data can then be played back to stimulate selected components. All data received from the helicopter over either data link is stored in this manner during flight.

D. Simulation Tools

Early in the GTMax system design, the top-level simulation requirements to support the development and operation of an experimental UAV were to

1) Test all custom developed research software and guidance, navigation, and control algorithms in a rigorous manner (more extensively than practical or safe in a flight test setting).
2) Test onboard computer hardware, operating system implementation, and software execution in real-time.
3) Rehearse all procedures and flight test plans.
4) Visualize recorded flight test data.
5) Reconstruction of flight test events after-the-fact (e.g., incident reconstruction).
6) Ask whether it can be utilized at the flight test location.

From these, the following component requirements were derived: 1) models of the sensors, aircraft, and aircraft interfaces — down to the level of binary serial data (i.e., packets) with time delays; 2) injection of model error and environmental disturbances, of those expected to be experienced in flight and worse; 3) flexible scene generation capability; 4) ability to operate a configuration of the simulation tools effectively using a single conventional laptop computer; and 5) reconfigurable data communication routines (previously discussed) in the context of flight software.

The simulator tools that have been developed normally run on high-end personal computers or laptops that use the Windows 2000/NT operating system or Linux, and is written primarily in C/C++. It includes an aircraft model, the aircraft interface model (YACS), and sensor models (IMU, GPS, sonar, magnetometer, YACS, and camera). The aircraft model has six rigid-body degrees-of-freedom plus engine, fuel, landing gear, and rotor dynamics. The helicopter interface, YACS, model simulates the servo interface unit functionality and RS-232 serial interface. The sensor models include errors, mounting location and orientation, time delays, and digital interfaces. The scene generator includes a three-dimensional graphics window (see Fig. 4) showing the aircraft and the terrain, and has additional functionality to aid in data visualization or use in the Ground Control Station.

The basic simulation tools allow for real-time display of all onboard data, including plotting and logging. It also allows one to modify any data. The simulator can run in real time or in a batch mode (faster than real time).

Between the generic communication routines and models for all system components, an extremely large number of simulator configurations are possible. The configurations include an all software configuration, SITL, where only the real flight software is utilized. Many combinations of real hardware and simulated components are possible, including testing only the primary flight computer hardware, only the secondary computer hardware, only the ground station, only a single sensor, or any combination of one or more of these.

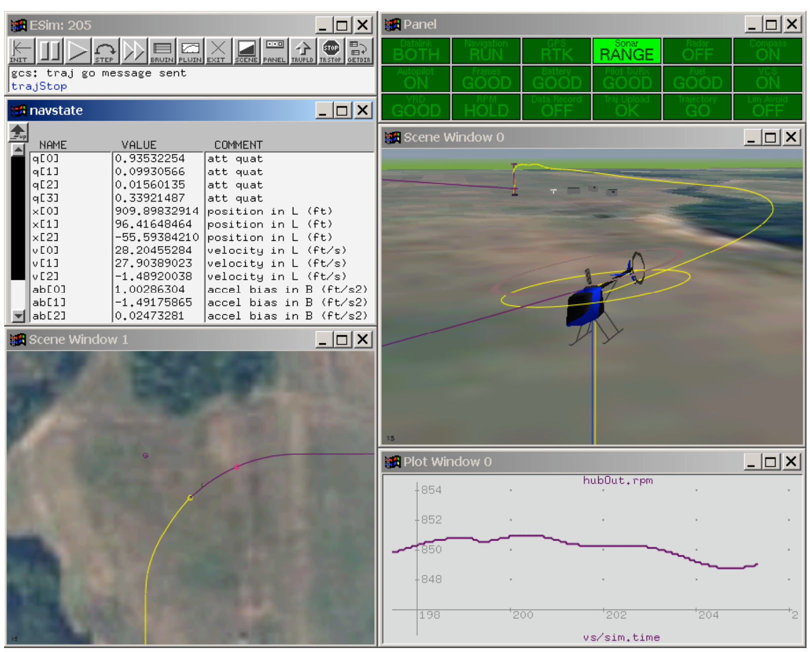

Fig. 4 Simulator scene generator and its use as a part of the Ground Control Station (GCS) operator interface.

III. System Integration Process General Guidelines

The system integration process for a single research test flight that involves changes to the baseline system involves five major steps: 1) develop test plan, including definition of test objectives; 2) define and implement of changes to baseline hardware software; 3) perform a SITL simulation test; 4) perform HITL simulation test(s); and 5) execute flight testing and data reduction. Earlier steps are repeated if a simulation or flight test fails in some manner. The complete process can take any length of time depending on the nature of the test or system change, even on occasion all on the same day.

To utilize the common-form of the SITL simulation configuration, illustrated in Fig. 5, the uncompiled software source code, which normally runs on the onboard computer, is compiled into the simulation tool itself, allowing this software to be tested on the simulation host computer. This allows all flight software to be tested without the need to tie-up any flight hardware. The majority of research software development can be conducted using this configuration, because it can be used on most desktop computers or laptops. Because this simulation tool includes detailed software interfaces and data communication system properties, the amount of time spent doing HITL simulation and tying up the flight hardware is effectively minimized.

Once any modification has been tested with the SITL configuration, any required HITL simulation configurations are used. The configurations required depend on what is being tested, but a test of a change to the primary flight computer is shown in Fig. 6. For this HITL simulation, the onboard computer is plugged into a simulation-host computer. Here, the hardware under test is the onboard computer(s) servos, along with all software that executes on the computer(s). The sensor and helicopter interface models provide the proper interfaces to the onboard computer, so the onboard computer configuration is identical to that used in a flight test. This HITL simulation configuration is used to test all guidance, navigation, and control algorithms software and the primary flight computer hardware, in real-time.

Another important configuration is the secondary computer HITL. In this configuration, the simulation host includes the primary flight computer software, the GCS, and the simulation. It then communicates with the secondary computer under test.

GCS test. When there are changes to the GCS or the datalink, the GCS can be tested as HITL. This allows an operator and the GCS hardware to interact with a simulated vehicle in the same way it is used in flight. The GCS and onboard software/vehicle models can be run on two separate machines on a network. This allows all the details of communicating data between the GCS and the onboard computers to be tested thoroughly before tying up flight hardware.

Truck testing of navigation system. This configuration has been used to test the onboard navigation software operating with the actual sensors without flying the vehicle. This was accomplished first statically, and then dynamically on a truck. For some of these tests a laptop has acted as the onboard computer (enabling easier access to data, because the GCS and onboard software were running on the same machine) as well as the actual flight computer.

Navigation data playback. Once onboard raw sensor data had been recorded in flight, extensive use of this data has been made in improving the navigation system. This was done by playing back this data in real time or faster than real time, and executing the onboard navigation flight software.

Fake GPS data in the lab. Prior to any flight test activity, it is important, as a final check, to bring up the flight software in the exact flight configuration to test basic functionality statically on the ground. Because this is conveniently done indoors, there may be no GPS data available. To facilitate this test, simulated GPS data is sent from a simulator running on some other machine on the network to replace data coming from the actual GPS receiver. This can be done for any other sensor that is temporarily offline.

Image processing configurations. Several programs have required simulator configurations that support testing of image processing subsystems. The first configuration used allowed still images (from flight or other sources) to be send one-at-a-time to the image processing subsystem running as part of the SITL configuration (on one or more networked machines). The second configuration utilized recorded video data from a flight test. To accomplish this, video was played back and sent to the onboard video server (the flight hardware) and then to the image processor. The image processor was either the flight hardware itself or an alternate networked machine, or even both when needed. The third image-processing configuration was used to test tracking and mapping algorithms and software. Here, the simulator generated fake video using the simulator scene generator. One way this was configured was to place a monitor in front of the GTMax onboard camera, utilizing the flight hardware for the camera, frame grabber, and image-processing computer.

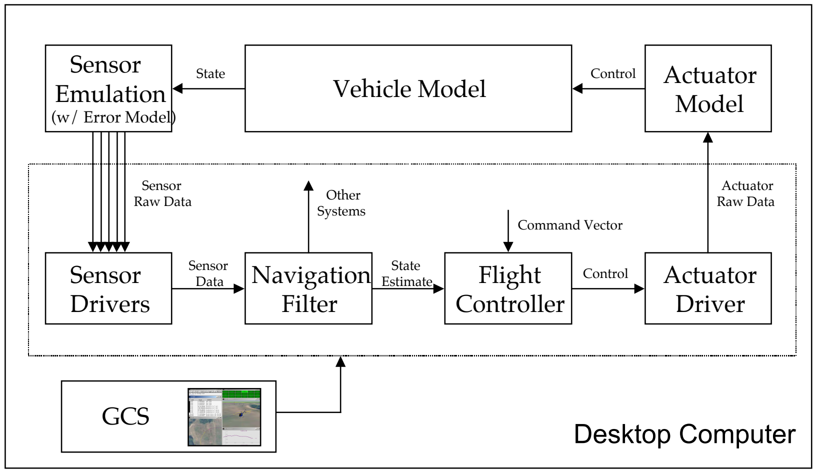

Fig. 5 Nominal software in the loop configuration.

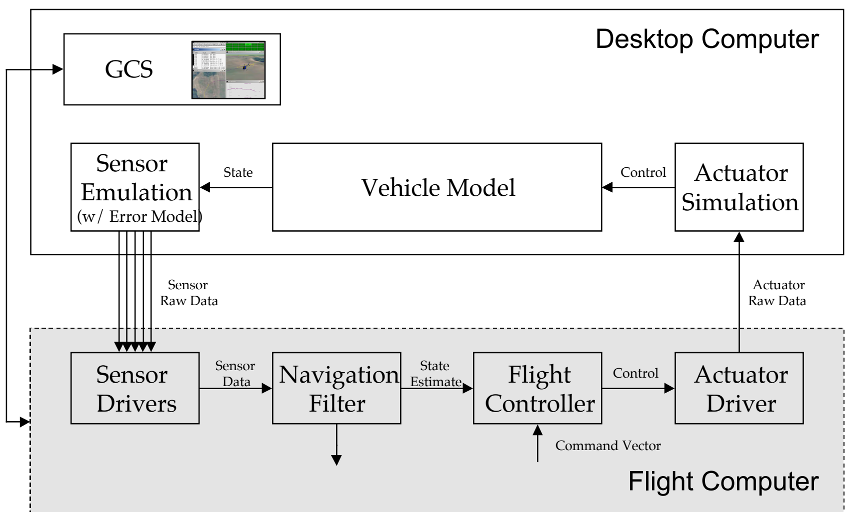

Fig. 6 Hardware in the loop structure for testing changes to the primary flight computer software or hardware.

GCS data playback. As stated previously, the communication routines can be configured to save and playback data sent over a serial line. All data received from the helicopter in flight is recorded in this manner, allowing for reconstruction of events in the case where all other data was lost.

IV. Research Flight Test Results

A number of research flight tests have been conducted on the GTMax, including the development of the baseline guidance, navigation, and control algorithms, SEC program tests and demonstrations, and the Aerial Robotics Competition mission. Selected results are summarized here.

A. Open Control Platform

The Open Control Platform (OCP)[12] was flight tested performing low-level flight control functions for the GTMax, including the reconfiguration of flight control software while the helicopter was in automatic flight. The architecture used is illustrated in Fig. 7, where the baseline software modules were configured as OCP software components, and two copies of the controller component were developed. The first used the nominal adaptive flight

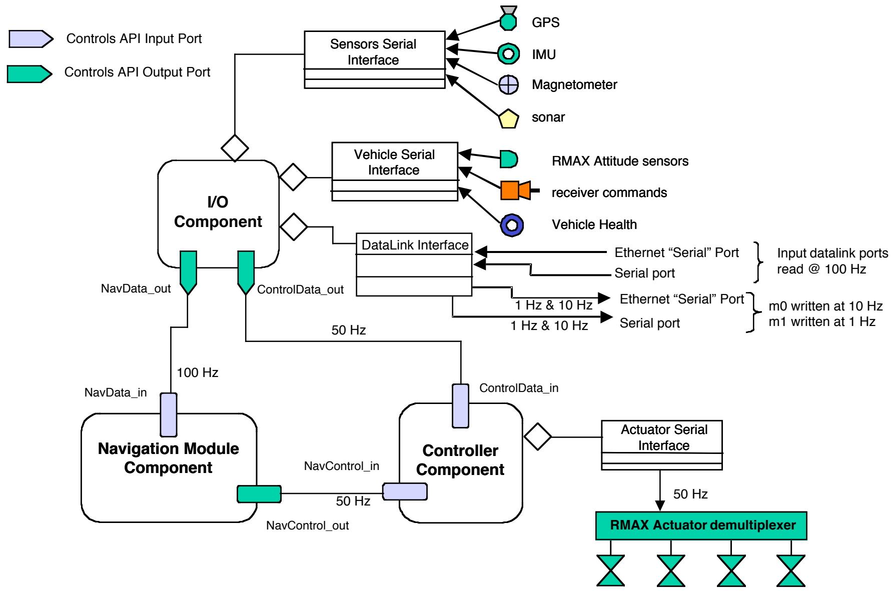

Fig. 7 Open Control Platform (OCP) implementation of baseline GTMax guidance, navigation, flight control, and communication.

controller; the second was configured as a conventional inverting controller. The OCP was able to swap between these two controller modules in real time, even with components running at 50 and 100 Hz.

B. Neural Network Adaptive Flight Control

A Neural Network (NN) adaptive flight control system that tracks desired helicopter trajectories has been tested extensively on the GTMax.[14] The system includes the ability to handle large model errors. For these tests, a simple linear model corresponding to the hover flight condition is the only model information provided a priori to the system. Online training of the neural network is relied upon to correct for the resulting model error over the entire speed flight envelope of the helicopter. The system also inherently accounts for actuator position and rate saturation as well as time delay.

A typical result is shown in Fig. 8 for a "racetrack" pattern viewed from above flown at 40 ft/s, and can be viewed in the attached video file. This trajectory starts and finishes in hover and includes normal turns at each of four waypoints. The maximum distance between the commanded and estimated position is approximately 10 ft, with average errors much lower. Figure 9 illustrates a typical speed trial, in this case reaching a maximum ground speed of approximately 95 ft/s, and can be viewed in the attached video file. The first leg is upwind, the second downwind. On the upwind leg the speed is limited by saturating collective pitch. Rotor RPM is held constant throughout at approximately 850. Aggressive maneuvers have also been tested, including a reversal of course, starting and finishing at 50 ft/s. The maneuver takes approximately 6 s, and allows the helicopter to come to a stop in approximately 75 ft, and involves a pitch attitude in excess of 60 deg, and can be viewed in the attached video file.

C. Automatic Takeoff and Landing

Automatic takeoffs and landings have been performed using the NN adaptive flight control system described previously.[14] The navigation system determines if the helicopter is on the ground by comparing the altitude above ground level (AGL) with a preselected value. That is, if the helicopter is within a few inches of the ground it acts as though it is in contact with the ground. Commanded position is slaved to the current position when the helicopter is declared on the ground. Also, the internal states of the flight control system are frozen. Depending on whether the helicopter is attempting a takeoff or a landing/hold, the rotor RPM is ramped either up to flight speed or down to idle respectively. Also depending on objective, the collective pitch is ramped up or down at a constant rate. Takeoffs are performed by ramping rotor RPM and collective until the helicopter is detected airborne, at which point the trajectory generator produces a smooth climb trajectory. Landings end with a slow vertical descent command until ground contact is detected and rotor RPM and collective pitch are reduced to an idle state.

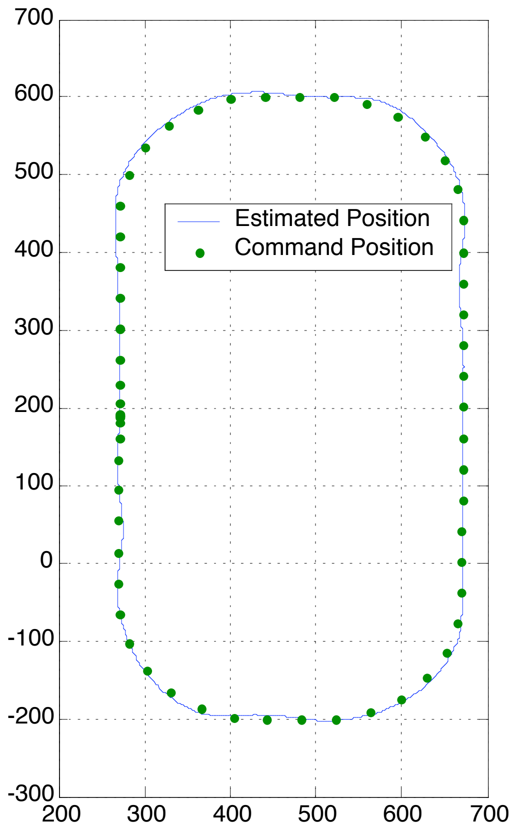

Fig. 8 Racetrack pattern flown at 40 ft/s starting and finishing in hover, commanded position plotted once per second

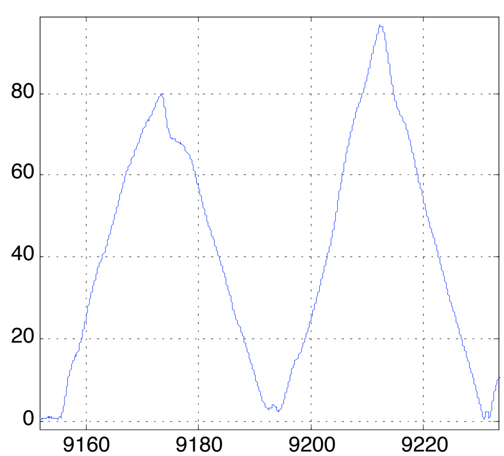

Fig. 9 Speed trial, first upwind (left) then downwind (right); speed limited by saturating collective upwind on first leg.

A plot of the first automatic takeoff of the GTMax is shown in Fig. 10 and can be viewed in attached video file, where a smooth climb to 30 ft of altitude and a hover were specified. The first automatic landing and the GTMax is shown in Fig. 11 and can be viewed in attached video file, where in this case a long slow descent of 0.5 ft/s is used until ground contact is detected.

D. Automatic Flight Envelope Protection Biographies

An automatic flight envelope protection system that utilizes an online trained NN to predict and then avoid flight envelope limits. Flight tests conducted to date include avoidance of a rotor stall prediction parameter (Erits factor, in units of speed), set artificially conservative to facilitate safe testing.[15] The limit itself is avoided by modifying the commanded trajectory acceleration, with commanded velocity and position also modified accordingly. A typical result is shown in Fig. 12. The OCP was utilized to manage this software module on the secondary flight computer.

E. Fault Tolerant Control

The fault scenario of a stuck collective pitch actuator was simulated in flight by limiting the deflection of swash plate actuators in such a way to prevent changes in collective pitch. The range of acceptable rotor rpm command was experimentally determined to be 700–950 rpm, all utilizing the baseline adaptive flight controller without modification (normally rotor rpm is 850). Note that flight at 700 rpm required saturated collective pitch in order to hover.

A fault tolerant control module was developed, running with the OCP on the second flight computer, generated a rotor RPM command that allows the existing flight controller to continue to function, albeit at reduced performance. It was demonstrated that this capability could be enough to safely recover the vehicle in such a scenario.

A typical flight test result is illustrated in Fig. 13; where up and down step responses of 10 ft were performed in between hover segments. Altitude hold performance is significantly worse without collective pitch, but still effective. Performance was not degraded significantly in other axes of flight control even though no changes were made to these other elements.

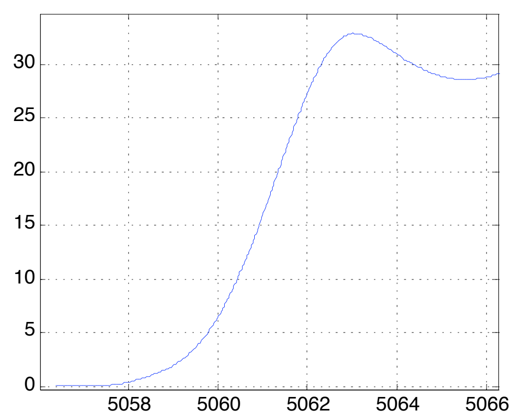

Fig. 10 Recorded altitude during an automatic takeoff and climb to a hover at 30 ft of altitude.

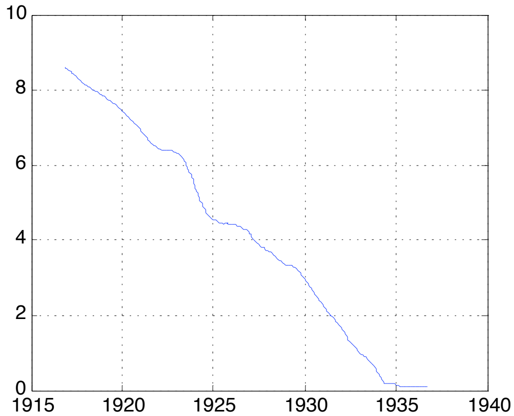

Fig. 11 Recorded altitude during an automatic landing, after a descent at 0.5 ft/s.

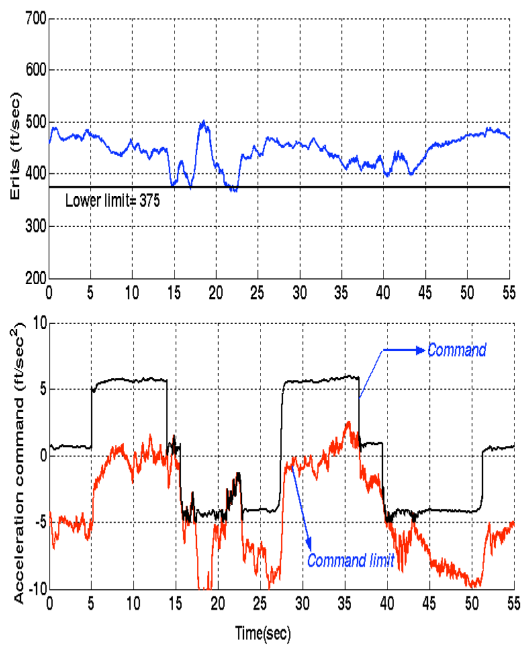

Fig. 12 Erits factor limit (a prediction of blade stall) is avoided by modifying the commanded trajectory acceleration.

F. International Aerial Robotics Competition Mission

In August 2002, the GTMax system was used to compete in the AUVSI International Aerial Robotics Competition.[16] For this competition, a UAV system must automatically identify a specific building in a prescribed search area, and then identify an opening into the building. This must be done without any human assistance during a mission attempt, and represents a high-mark for UAV automatic search and recognition capabilities. A camera and frame grabber were added to the basic GTMax, and the second computer was configured as an image processing subsystem running the Linux operating system. Mapping and flight planning software components were added to the primary flight computer. Because of radio frequency interference at the contest site, multiple attempts had to be aborted due to loss of GPS lock. On the one attempt that was able to proceed to its conclusion without loss of GPS,

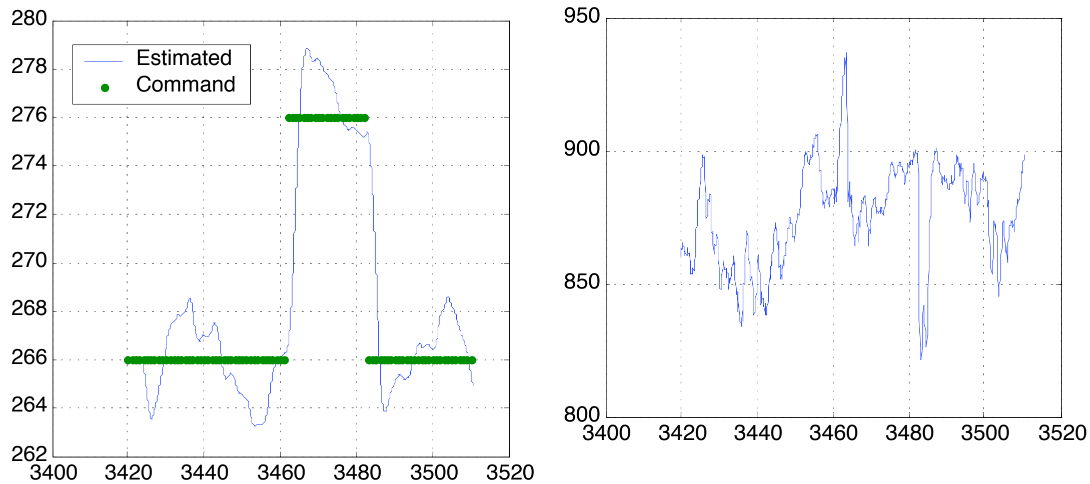

Fig. 13 Utilizing rotor rpm to accommodate a simulated stuck collective actuator, step responses; (left) altitude and altitude command, (right) measured rotor rpm; note transient in rpm during climb and descent.

Fig. 14 (top) Typical image of symbol (black circle with white "X") used to automatically identify building, raw on left, a processed image with green "+" on symbol on right; (bottom) automatically selected opening to this building is the door in the center of the image.

the system descended down to 50 ft of altitude and circled each of the three buildings looking for the identification marking and openings into the building. On this attempt, the correct building was identified, but the opening automatically selected was from a neighboring building.

In July 2003, with the mission now moved to the McKenna MOUT site with its 15 buildings, an improved system was tested.[1] The improved system utilized the now-baseline pan/tilt/zoom camera system and improved image-processing software. Four attempts were made during the competition, on three of those attempts, the system automatically flew a search pattern over this simulated European village, looking at all of the walls of all of the buildings within. Three times, it automatically located the pre-specified sign on one of the buildings and identified the correct "building of interest." Recorded images are shown in Fig. 14. The vehicle then automatically flew a search pattern looking for openings into this building, and then gave the location of a valid opening along with a picture of that opening, also shown in Fig. 14.

V. Conclusion

The extensive use of a variety of simulation configurations has been of considerable benefit for the recent development and operation of the GTMax UAV, and for its use in research. The key features of a flexible data communication system, models for all hardware components, and a simulation software infrastructure enable these configurations. The benefits have included increased safety, effective participation of a large number of researchers, the detection of errors early thus saving development time, and the effective use of flight test data.

The use of a modular avionics architecture and the use of a reliable vehicle with a relatively large payload capacity allows the GTMax to be configured quickly for a variety of experiments. For example, it allowed the vehicle to be reconfigured for the aerial robotics competition relatively easily by adding a camera and video server. The capacity also allows efficient use of flight test time, allowing multiple unrelated flight test points during a single flight.

In terms of results, the research UAV system described here has been utilized to test new software infrastructures for control, adaptive flight control in aggressive flight, fault-tolerant control, automated envelope protection, and automated search and recognition. These results were obtained through approximately 100 flights spread over 23 days of flying in a 16 month period.

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