THE NASA URBAN AIR MOBILITY TESTBED FLIGHT RESEARCH AIRCRAFT

Charles T. Howell[*] and Kevin J. Shelton[†]

The National Aeronautics and Space Administration (NASA) is leading government, industry and academic research effort known as Urban Air Mobility (UAM). The UAM activity goal is to develop the technology needed to make possible an urban air transportation system that makes use of human-crewed and crewless vehicles using automation, artificial intelligence and other technologies to safely and efficiently air transport people and goods within an urban environment. The NASA Langley Research Center (LaRC) created a UAM Flight Research Testbed Aircraft from a Cessna LC40 general aviation aircraft. The testbed has updated digital avionics and research systems needed to conduct flight research. The aircraft has two separate autopilots; a standard Federal Aviation Administration (FAA) certified system, and a modified research autopilot. The research autopilot has modifications that allow increased authority and enhancements to allow more automation and artificial intelligence controls. A network of three research computers hosts software to research several activities including automated air traffic sense and avoid, ground collision avoidance and obstacle avoidance. These UAM research activities involve automation and artificial intelligence technologies developed at three NASA centers. The NASA Langley, NASA Armstrong, and NASA Ames Research Centers are working together to develop and test these UAM technologies. This paper provides details of the systems, capabilities and research projects of the UAM Testbed Research Aircraft.

INTRODUCTION

The UAM concept, the idea of small vertical takeoff and landing vehicles used for short-range transportation in an urban environment is becoming a universal concept that is generating interest from a diverse set of institutions around from the world. Academic, government, commercial, and military institutions are realizing the potential uses of the UAM technology. Several international partnerships have formed to research UAM technologies. Some of these partnerships involve some of the most significant aerospace entities including Boeing, Airbus, Bell Helicopter, Honeywell and others. On the US government side, NASA, the FAA, and several corporate and academic

[*] Flight Test Integration Engineer, Research Services Directorate, NASA Langley Research Center, Hampton, VA.
[†] Flight Test Integration Engineer, Research Services Directorate, NASA Langley Research Center, Hampton, VA.

institutions are working together to research the technologies to make UAM possible[‡]. The collective interest and potential benefits of UAM make the possibility of moving forward very real. NASA is sponsoring and providing funding for the UAM Testbed Flight Research Aircraft through the Flight Demonstration Capabilities (FDC) Project. This project conducts complex and integrated flight research demonstrations in support of NASA's Aeronautics Research Mission Directorate (ARMD) programs[§]. FDC also operates, sustains and enhances the specific flight research and test capabilities from test aircraft to full flight-test ranges needed to achieve technical goals in ARMD's Strategic Plan[**]. FDC supports other NASA mission directorate activities and national strategic needs. One of the goals of FDC is to promote the development of safety-related aeronautics technologies via selected flight-test research projects. The FDC supports the use of NASA developed Autonomous Flight Safety Systems (AFSS) to enhance UAM safety. The AFSS is an autonomous system that analyzes sensor data in real-time to detect abnormal and other safety-related conditions. Originally developed for NASA unmanned rocket launches, AFSS autonomously determines if flight termination conditions exist using onboard sensor data[††]. Many technologies must develop to make UAM safe and efficient. These technologies include automation, sense and avoid (aircraft, ground, buildings, and towers), air traffic control, aeronautics, energy storage, and other related technologies. The Testbed Research Aircraft will aide in the development and testing of these technologies.

BACKGROUND

The UAM Testbed Research Aircraft is a Cessna LC40 (Figure 1) that was initially a Lancair Columbia 300 before Cessna bought Columbia Aircraft in 2007. NASA Langley purchased in 2001, the Cessna LC40, a Cirrus SR22, and a Cessna 206 to serve as general aviation research aircraft. The LC40 and SR22 aircraft are very similar in size, weight, composite construction, performance. Continental IO-550 supplies engine power for both aircraft. The NASA Langley Small Aircraft Transportation System (SATS) research program acquired all three aircraft, and all three received some research modifications, but only the Cirrus performed SATS research. The SATS program studied methods and technology to make better use of small and under-utilized airports. However, available funding, personnel, and other resource limitations caused the program to choose one aircraft to perform SATS flight research. Selected to receive most of the SATS research modifications, the Cirrus became the only aircraft that performed SATS research projects. The SATS program ended in 2005 and all three aircraft participated in other NASA Langley research experiments before the LC40 entered long-term storage due to lack of work.

[‡] Norris, Guy (2018, November 8) NASA Rolls Out Urban Air Mobility 'Grand Challenge' Plan. *Aviation Week & Space Technology,* Page 16

[§] Gipson, Lillian. "Flight Demonstration and Capabilities (FDC) Project." *NASA*, NASA, 9 May 2016, www.nasa.gov/aeroresearch/programs/iasp/fdc.

[††] Bull, J.B., Lanzi, R.J., 2007, An Autonomous Flight Safety System, American Institute of Aeronautics and Astronautics 092407, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080044860.pdf (March 3, 2019)

Figure 1. The Cessna LC40 UAM Testbed Flight Research Aircraft.

AIRCRAFT HARDWARE MODIFICATIONS

Avionics Upgrade

In 2016, it was determined there was more general aviation research that could be handled by the Cirrus SR22 alone, and the LC40 was needed. The reactivation of the LC40 included a complete avionics system upgrade. Upgrades to the LC40 Research System included some of the latest digital technology. The removal of the old United Parcel Service Aviation Technology (UPS-AT) avionics systems made room for the installation of new Garmin 600 and 700 series digital avionics system upgrades to the aircraft.

In its original research configuration, a separate research alternator in the Lancair provided separate and isolated electrical power to the research system. As part of the aircraft upgrade, an upgraded aircraft alternator went from 70A to 100A, with 30A dedicated to the research systems to allow removal of the research alternator. Removing the research alternator reduced the aircraft complexity and saved 100 pounds of weight (alternator, mount, battery, power contactor, and wiring). The extended storage caused internal engine corrosion and other problems requiring a new engine. A new engine procurement preceded the engine installation and the successful break-in flying.

The original aircraft 1990’s era avionics suite included United Parcel Service-Aviation Technologies (UPS-AT) communications and navigation equipment. The original avionics consisted of non-digital instruments and the S-TEC 55 autopilot. The avionics upgrades included a Garmin GDU620, GTN750, and GTN650 for the primary and secondary avionics systems. Other upgraded components include the Garmin GTX345R ADS-B Transponder, a GRS77 Heading Reference System (AHRS), a GMU44 Magnetometer, a GDC74 Air Data Computer (ADC), and a GMA35 Audio Panel. An S-TEC 55X Autopilot installation provided an upgrade to the original S-TEC 55 model. Figure 2 shows the aircraft instrument panel with the upgraded avionics.

Research System Upgrade

The original research system implemented during the first two years after the aircraft purchase in 2001. Except for the Research Equipment Pallet and the Power Distribution Panel, all of the remaining research components were obsolete. All new systems were part of the upgraded Research System. The new systems included a United Electronic Industries 6-slot, Ethernet-based Data Acquisition, and Control Cube as the heart of the upgraded system. This data acquisition system (DAS) provides centralized data acquisition from a variety of interfaces including analog, digital and serial data sources and distribution of all collected data over Gigabit Ethernet to research computers and other networked devices. A dedicated connection to the aircraft Garmin digital avionics via ARINC 429 and RS-232 serial interfaces allows for the collection of aircraft position, attitude, air, acceleration, and other state data as well as Automatic Dependent Surveillance-Broadcast (ADS-B) data.

Three new computers made up the upgraded research computer system. Two of the new in-house built computers have commercial ASUS H170 mini-ITX motherboards as the main component. An Intel Core i7-6700, 3.4GHz processor, 16-GB memory, a 500GB, M.2 boot solid-state drive, and a 500GB SATA solid-state drive were the main components installed on each motherboard. The two computers were set up for dual boot capability between the Linux and Windows operating systems to serve as hosts for research software applications. The third research computer is an ODROID-XU4 single board computer to serve as a dedicated processor for automation, artificial intelligence, and safety-related functions. The ODROID-XU4 computer significant components include a Samsung Exynos5422 Cortex™-A15 2-GHz processor, a 16-GB solid-state boot drive, and an SD-Card slot for additional memory. The ODROID contains external interfaces including Ethernet, Wi-Fi, and Bluetooth. All three computers are part of a Gigabit network along with the data acquisition system and other research systems.

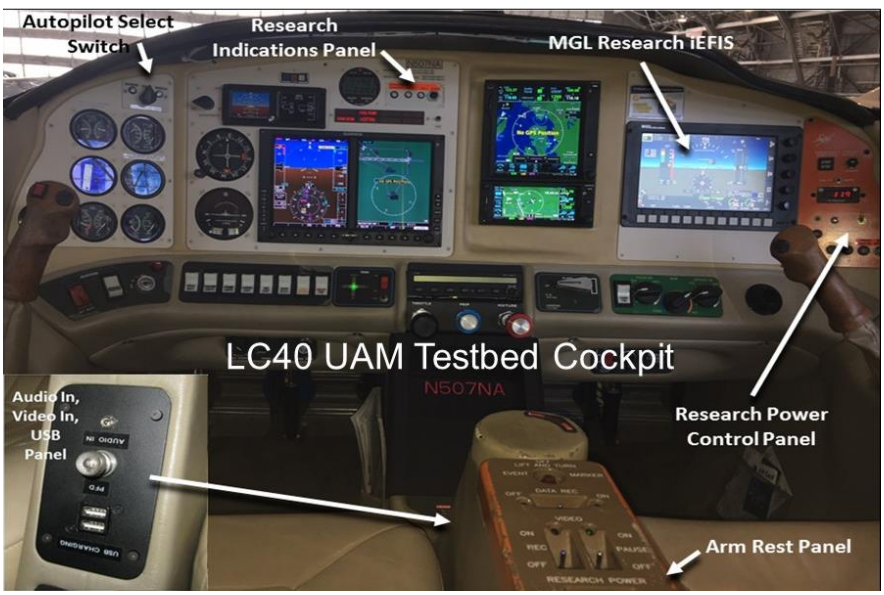


Figure 2. Cessna LC40 Upgraded Instrument Panel.

Other Research System upgrades include a Netgear GS108 8-Port Gigabit Switch to connect all of the network components. A Masterclock GMR-1000 Network Time Protocol (NTP) Time Server and Time Code Generator is used to allow the time synchronization of the computer clocks to Universal Time Coordinated (UTC). A keyboard, video, mouse (KVM) switch is installed to allow the Research Systems Operator (RSO) to switch between computers. Two GoPro Hero 4 video cameras provide for the recording cockpit and outside aircraft activity. The GoPro high definition video is overlaid with GPS derived text messages by two Video Logix Proteus Video Overlay Systems. This system can overlay the GoPro video with time, position, altitude, velocity and other data from National Marine Electronics Association (NMEA) RS-232 serial messages. An Odessey7+ video recorder and monitor provides for viewing and recording the GoPro video, overlaid text, and aircraft cockpit intercommunications audio.

Additional research systems include a Novatel ProPak 638 multi-frequency, multi-constellation, precision Global Navigation Satellite System (GNSS) receiver and two GoPro Hero4 video cameras. The C-band and S-band telemetry systems are capable of sending high definition video, audio and Ethernet data to the ground-based Flight Operations and Support Center (FOSC). Installed in the cabin is an interface connector to allow the research systems to receive digital data from the Garmin avionics systems including air data, position, ADS-B, attitude, velocity, acceleration, and other data from multiple avionics serial data sources. Figure 3 shows the Research System components mounted in the Research Equipment Pallet.

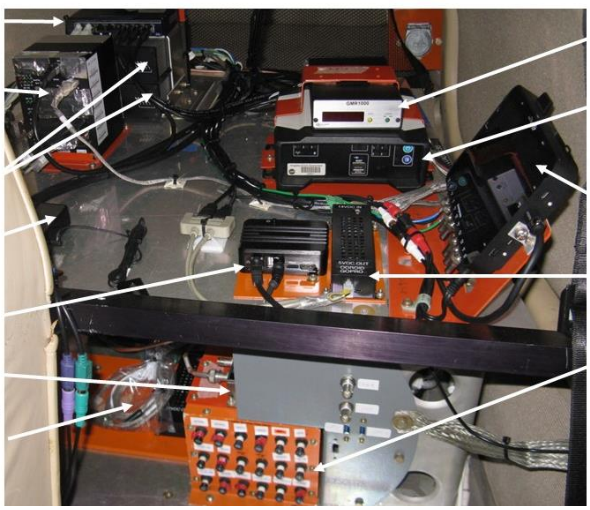


Figure 3. Research Equipment In Research Equipment Pallet.

MGL Autopilot Installation Considerations

The LC40 standard autopilot is an S-TEC 55X standard FAA certified unit. Standard certified autopilots have limited force authority, rates, and bank angle limits to allow the pilot to override all autopilot commands. Certified autopilots can only command the standard rate (two-minute) turns. The FAA specifies autopilot limitations as part of the autopilot certification process. The UAM flight test requirements specify higher autopilot force authority and the ability for higher turn rates and higher bank angle limits. The NASA Armstrong researchers recommended the MGL Avionics iEFIS Explorer 8.5” advanced electronic instrument system for installation in the aircraft.

The decision was made to install the MGL system in parallel with the existing S-TEC 55X autopilot. This option presented the flexibility of having a certified autopilot for use during non-research flights and a customizable research autopilot for research flights.

MGL Avionics makes non-FAA certified avionics systems for the homebuilt, experimental and ultra-light aviation markets. The MGL avionics systems are full-featured, digital, and state of the art flight, navigation, and engine monitor systems with a built-in autopilot. Hundreds of the MGL avionics systems are flying and are very popular with the homebuilt enthusiasts. Another reason for the MGL choice is the relationship of the NASA Armstrong researchers with MGL Avionics. NASA Armstrong researchers searched for an autopilot manufacturer that was willing to modify an existing autopilot to produce a capable research system with customizable features. Armstrong researchers were able to form a collaboration with MGL Avionics to perform the desired modifications.

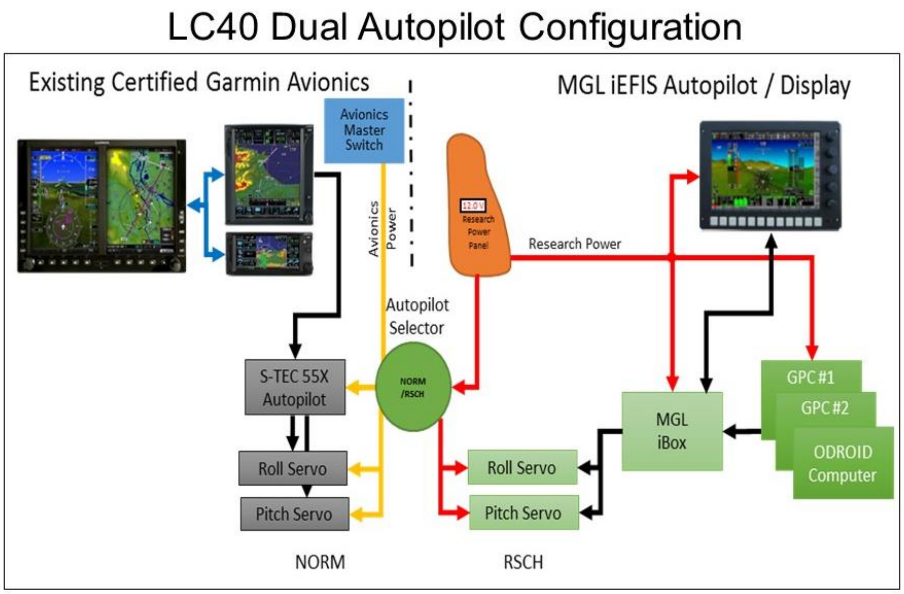


Figure 4. Standard and Research Autopilot Switch.

MGL Research Autopilot Installation

Considerable time and effort went into determining the best method to implement the MGL research system into the aircraft. One option was to remove the S-TEC system and replace with the MGL system. This option allows for research flights where the customizable autopilot adjusts to match the desired research flight-testing conditions. However, the modified research autopilot is not desirable for regular non-research flights. By consensus, the best option was to install the MGL system and keep the S-TEC system. This option requires a method to ensure only one system is active at a time and a positive, unambiguous indication to the pilot of the active system. Considered the most desirable option, a dual autopilot, parallel installation with a mutually exclusive selection of the autopilot was implemented.

A circuit that allows switching between the two autopilots was designed, fabricated, and installed in the aircraft instrument panel. The Autopilot Switch provides a means to ensure that aircraft power is applied only to the servos of the active (selected) autopilot. The system ensures that no power is supplied to the inactive (unselected) system. Shown in Figure 4 is the autopilot switching system configuration. Additionally, the system provides a visual indication of the active system in clear view of the pilot as shown in Figure 5. The aircraft Safety Pilot uses the switching system to switch the autopilot systems as required during the flight test. Figure 8 shows the Autopilot Switch truth table.

Figure 5. Autopilot Switch and Annunciators.

The original S-TEC 55X Autopilot is a two-axis (pitch and roll) system, and the MGL pitch and roll servos installation must allow both servos to work. A mounting structure was designed, fabricated and installed to hold the MGL pitch servo near the S-TEC servo. The S-TEC pitch servo connects to a capstan that connects via cable to a pushrod connected to the horizontal stabilizer bell crank. The MGL pitch servo connects to the horizontal stabilizer bell crank via pushrod from the MGL pitch servo. An engineered and fabricated attach point installed on the stabilizer bell crank provides an attach point for the MGL servo. Figure 6 shows the MGL pitch servo installation.

The MGL roll servo installation is similar to the pitch servo. The installation of an engineered and fabricated mounting structure provided a place to hold the MGL roll servo. An engineered and fabricated attach point allowed for the installation of the MGL roll servo pushrod on the roll assembly. Shown in Figure 7 is the MGL roll servo installation. The MGL servos are digital and programmable for the desired torque from 1.8 ft-lbf to 21 ft-lbf. A force of 10 ft-lbf was determined to be adequate to move the control surfaces and allow override by the pilot. The MGL system allows for programming the desired force levels and other settings in non-volatile memory for recall at system turn on. The MGL system also has a feature to automatically execute pitch and roll surface movements in the positive and negative directions. This feature is advantageous during preflight and other ground system checks.

MGL Autopilot Flight Testing

After the installation of the MGL system and successful ground testing, the MGL system was ready for flight-testing. The flight test goal was to verify proper operation, make any necessary adjustments, and determine if any interference exists between the S-TEC and MGL systems. Flight control system interference was mitigated by disconnecting the MGL servo to flight control linkages for the first flight. The MGL servos were connected but unpowered for the first flight. This configuration assisted with the evaluation of the S-TEC autopilot and flight controls for proper operation. The S-TEC autopilot performed nominally and with no observed discrepancies. The MGL linkages were connected to evaluate the MGL system during the next and subsequent flights.

The MGL iEFIS installation documentation specifies a set of tests during flight to verify settings for both the pitch and roll servos. Roll servo settings for rate of turn, torque, bank servo magnitude, left/right bank limits, and heading control must be set and verified for proper operation. Some of the MGL autopilot settings cannot be changed in flight and must be observed and tested in flight and adjusted on the ground between flights. MGL recommends a set of initial settings for both servos that can be adjusted based on flight test results. The pitch servo adjustments include low and high airspeed settings, vertical speed settings for ascent and descent, torque, pitch control magnitude, and pitch change to vertical speed reaction[‡‡]. It took several flights to test, verify, and adjust all of the MGL autopilot settings. Testing was performed to look for any excessive friction, binding, or stiffness caused by the MGL installation. The MGL autopilot was declared operational and ready for flight research after the testing and adjustment flights.

Figure 6. MGL Pitch Servo Installation.

‡‡ MGL Avionics, 2014, iEFIS Integrated Autopilot User and Installation Manual, http://kb.mglavionics.com/article/AA-00296/7/EFIS/Autopilot-Manuals.html (March 4, 2019)

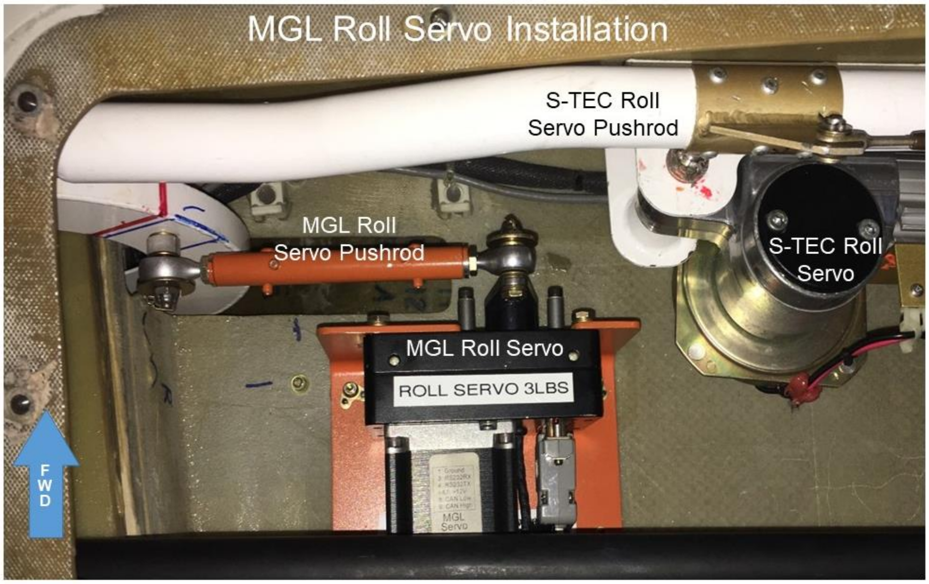


Figure 7. MGL Roll Servo Installation.

RESEARCH SOFTWARE

MGL Autopilot Firmware Modifications

NASA Armstrong entered a partnership with MGL to make modifications to the MGL system to make it into a configurable flight research tool. The modifications allow changing the MGL internal autopilot limits, rates, gains, and other parameters to support the goals of the research flight tests. Another MGL modification is the development of a serial interface to allow sending external autopilot commands and receiving state and other MGL data over an RS-232 serial interface. The serial interface allows sending turn commands along with target bank angle and turn rate to the MGL autopilot. The interface provides for external climb and descent rates, target altitudes, and waypoint coordinates. These changes make it possible for the UAM research systems and software to control the aircraft to make the necessary collision avoidance and other required maneuvers. At this writing, the MGL software modifications are still under development and not yet ready for delivery.

Expandable Variable-Autonomy Architecture (EVAA)

The Expandable Variable-Autonomy Architecture (EVAA) is a modular software framework that incorporates the ability to tailor its use to the aircraft platform. EVAA provides autonomous systems safety protections to the aircraft type, fixed wing or rotor, manned or unmanned. For the initial integration of EVAA with the MGL autopilot, only the improved Ground Collision Avoidance System (iGCAS) will be incorporated within EVAA. In subsequent phases, additional safety monitors such as GeoFence, air collision avoidance, and Forced Landing System may be considered or testing[§§]. Listed below are components of EVAA:

[§§] Norris Guy (2016, March 28) NASA's Traveler To Demo 'Trustworthy' UAS Autonomy. *Aviation Week & Space Technology*,https://awin.aviationweek.com/ArticlesStory.aspx?keyWord=NASA%27s%20Traveler%20to%20demo%20trustworthy%20UAS%20autonomy&id=2f676221-a776-4d39-ab2a-0a2d08be2869 (March 20, 2019)

• Improved Ground Collision Avoidance System (iGCAS): Includes both terrain and obstacle avoidance.

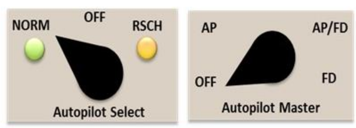
• GeoFence: Virtual boundaries (vertical and horizontal) that aircraft is to avoid.

• Forced Landing System (FLS): In the event of aircraft failure, FLS is designed to determine the "best" landing location.

• Flight Executive (FE): Besides essential EVAA system health monitoring, the FE contains one of the most critical functions: the Moral Compass. This module receives data from multiple safety monitors such as iGCAS, GeoFence, and FLS. In the event of multiple safety monitor violations, the Moral Compass decides in which order to act on these monitors based on an established user-defined consequence value.

• Flight Test Module (FTM): Provides test-specific capabilities such as user established terrain/obstacle buffers, provides the ability to turn the various safety monitors/recovery controllers on or off to improve test efficiency and is EVAA's interface module for the COTS autopilot waypoint follower.

Autopilot Select Switch Annunciator Truth Table



Autopilot Select	Ship Autopilot Master Functionality	S-TEC autopilot	MGL autopilot	AP Indications
OFF	DISABLED	DISABLED	DISABLED	OFF
NORM	All Functions ENABLED	ENABLED	DISABLED	NORM
RSCH	DISABLED	DISABLED	ENABLED	RSCH

Figure 8. Autopilot Switch Truth Table.

Integrated and Configurable Algorithms for Reliable Operations of Unmanned Systems (ICAROUS)

Flight research projects are in preparation at NASA Armstrong, Ames, and Langley for the UAM Testbed Research Aircraft. The planned first UAM flight project is the Integrated and Configurable Algorithms for Reliable Operations of Unmanned Systems (ICAROUS) project from NASA Langley. ICAROUS is an air traffic sense and avoid experiment. The ICAROUS flight test resumes where the Detect and Avoid in Cockpit (DANTi) flight-test research left off. The new work goal is to test the NASA-developed Detect and Avoid Alerting Logic for Unmanned Systems (DAIDALUS) algorithm and related displays in the aircraft research software instead of in the Linux tablet. The DANTi flight test successfully flew on the Cirrus and LC40 aircraft and in both cases aircraft state and ADS-B data was input from the aircraft research computers into the Linux tablet computer via Ethernet. The LC40 Research Computers will host the ICAROUS software instead of the Linux tablet as implemented in the DANTi flight test.

Improved Ground Collision Avoidance System (iGCAS)

The second flight test planned is the EVAA based iGCAS experiment from NASA Armstrong. This experiment is an automatic ground collision avoidance system. The EVAA/iGCAS automatically commands the ground collision avoidance maneuver via the MGL autopilot. A version of the iGCAS previously flew successfully on the Cirrus SR22 in 2013. At that time, the Cirrus was not capable of robust automatic escape maneuvers, and visual cues were provided to the pilot to perform the escape maneuvers manually. The MGL autopilot provides aircraft state-space data to EVAA over a serial interface. EVAA utilizes this information, together with EVAA-stored terrain and map data, to determine if a potential ground collision condition exists. EVAA continuously computes three-dimensional (3-D) escape trajectories in real-time that are projected forward in time and space. Upon EVAA, determining a ground collision is imminent, EVAA transmits a command to the MGL autopilot to execute one of three EVAA pre-planned iGCAS avoidance maneuvers. A straight climb, climbing left turn, or climbing right turn are the three collision avoidance maneuvers. EVAA calculates the required escape maneuver turn rate, bank angle, and climb rate. Situation information about potential terrain collision and EVAA-commanded avoidance maneuver is provided to the aircraft crew. Upon EVAA, determining the collision has been avoided, aircraft control is relinquished to the pilot or the system controlling the aircraft.

Automatic Voice Recognition and Response System

The planned third flight experiment is the NASA Ames Automatic Voice Recognition and Response System. The goal of this experiment is to automatically recognize Air Traffic Control (ATC) voice commands and generate automatic aircraft response with commands to the MGL autopilot. This experiment is to proceed in a phased approach with the first phase only listening and analyzing the recorded ATC voice commands. Later phases may couple to the autopilot if successful with the early phases. NASA Ames is developing this capability along with an Autonomy Operating System (AOS). The AOS is a computer operating system in development as a host for automation and artificial intelligence applications.

CONCLUSION

The LC40 aircraft is under development to serve as a UAM Testbed Flight Research Aircraft. The research tools including computers, sensors, software, and the MGL autopilot are in development and testing to serve during planned UAM research projects. The MGL flight-testing is progressing very well, and it appears that the system can perform as desired as a customizable research autopilot. The planned research experiments are progressing through the development and review process as required before flight-testing.