FROM IN-FLIGHT SIMULATORS TO UAV SURROGATES

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ABSTRACT

Calspan has been the worldwide leader in innovating, developing, and operating In-Flight Simulators (IFS) since 1947. Learjet IFS that have been used for over 30 years to train test pilots have found a niche in the last decade as effective Unmanned Air Vehicle (UAV) surrogates. The Learjet platform provides a safe way to test unmanned systems by providing a fully-programmable autonomous aircraft with an onboard safety pilot to take over in the event of a failure of the system under test. The Learjets have been instrumental in the development of Air Force and Navy Autonomous Aerial Refueling (AAR) and Sense and Avoid (SAA) programs. Configured as a Remotely Piloted Aircraft (RPA), the Learjets have been flown to touchdown by pilots “flying” from a ground station. The success of the Learjet as a UAV surrogate has prompted this capability to be extended to Calspan’s G-III Airborne Testbed which offers additional capacity to carry airborne systems as well as increased aircraft performance.

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INTRODUCTION

Calspan has been the primary innovator, developer, and operator of variable stability In-Flight Simulators (IFS) in the United States as well as the rest of the world since 1947.¹ The variable stability airplane was conceived as a device that would permit in-flight variation of the characteristics or flying qualities of an airplane so that a pilot could determine the suitability of these characteristics in actual flight. Today the concept of the variable stability airplane has progressed into true in-flight simulators which are routinely used as an extension of ground-based simulators to the flight environment and its real-world cues.
Calspan currently owns and operates 3 IFS Learjets (Figure 1): the first is a Learjet Model 24 that first flew in 1981; the second and third Learjets are Model 25’s that first flew in 1991 and 2007, respectively. A fourth IFS Learjet is currently in modification and is scheduled to enter service as an IFS in 2014. The first Learjet was originally conceived, designed, and modified for the purposes of training test pilots, conducting handling qualities research, and for the development of new piloted aircraft. Since then, the uses of these Learjets have expanded to include Upset Recovery Training (URT) where the Learjet is programmed to simulate actual aircraft upsets that have resulted in accidents in order to train pilots how to recover from these upsets.²

All of the original intended missions of these Learjets involved a pilot-in-the-loop flying the aircraft. In the past decade, these aircraft have also found use as effective Unmanned Air Vehicle (UAV) surrogates. In this role, the Learjet platform provides a safe way to test unmanned systems by providing a fully-programmable autonomous aircraft with an onboard safety pilot to take over in the event of a failure of the system under test. The Learjets have been instrumental in the development of Air Force and Navy Autonomous Aerial Refueling (AAR) and Sense and Avoid (SAA) programs. Configured as a Remotely Piloted Aircraft (RPA), the Learjets have also been flown to touchdown by pilots “flying” from a ground station.

**LEARJET IN-FLIGHT SIMULATORS**

The Learjets are highly modified (Figure 2) to provide three (pitch, roll, yaw) or four (pitch, roll, yaw, thrust) degree-of-freedom (DOF) IFS capability. The right pilot seat of
each Learjet has been extensively modified to serve as the Evaluation Pilot (EP) crew station. The normal Learjet wheel/column has been removed from this side of the cockpit and can optionally be replaced with one of three variable-feel controllers: a center stick, side stick, or wheel/column. The basic Learjet rudder pedals have also been replaced with variable-feel pedals. Each of these control inceptors has a programmable feel system which enables simulation and evaluation of a wide range of different characteristics (i.e. gradients, displacements, and non-linearities such as breakout). Electro-hydraulic servo actuators drive the aircraft’s primary control surfaces (elevator, aileron, rudder) in response to a combination of pilot inputs and signals sent from the Variable Stability System (VSS) computers to provide a full-authority fly-by-wire flight control system. Two of the IFS Learjets also have programmable auto-throttles that were installed specifically for UAV surrogate work. The left pilot station is reserved for a Calspan Instructor/Safety Pilot (SP) which has not been altered in any way and remains a fully reversible, mechanical control system. Additional sensors have been added to the aircraft to provide the VSS with input data including angle of attack and sideslip vanes, accelerometers, air data sensors, angular rate and position sensors, an Inertial Navigation System (INS), and Global Positioning Systems (GPS).

The VSS computers can be programmed directly in C or symbolically using Matlab™ Simulink. This makes the VSS a useful tool for rapid prototyping and allows for quick turnaround times when the system is reprogrammed. The architecture of the VSS allows easy interface with additional sensors, cockpit displays, data recorders, and computer equipment. The VSS can be programmed dynamically while in flight through the Configuration Control System (CCS) panel that provides the SP an interface to select the feel characteristics, command gains, feedback gains, and nonlinear characteristics. While engaged, the VSS controls the elevator, aileron, rudder, and throttles. EP inputs (or commands from a UAV simulation) are fed into the simulated flight control system which augments the Learjet dynamics to represent those of the vehicle being simulated. The VSS then calculates the Learjet surface positions required to achieve the desired aircraft responses. The results are used to drive the Learjet
surface servos, which operate independent of, but in parallel with, the normal Learjet control cables to move the surfaces. Because of direct mechanical connection, the SP’s controls move as a summation of the inputs applied to the surfaces by the EP (or UAV simulation) and the VSS, providing important tactile cues and response anticipation to the SP.

Safe flight is maintained by a Safety Trip (ST) system that operates autonomously but can also be initiated manually by either pilot. The VSS is automatically disengaged if a system failure occurs or if a sensor or load measurement (e.g. load factor or angle of attack) exceeds preset thresholds which are set a safe distance away from the actual Learjet limits. A manual ST can be activated by either pilot (usually by the SP) based upon their judgment using one of several manual ST buttons located in the cockpit. When a ST occurs, Learjet control reverts back to the SP who then flies the aircraft through the standard Learjet reversible flight control system. All VSS disengages are accompanied by aural and visual cues that provide a clear enunciation that control has reverted to the SP. On disengage, the Learjet smoothly transitions to the current trim condition of the Learjet minimizing any transients.

Two Flight Test Engineer (FTE) workstations are located in the aft cabin which provide for real-time changes to the simulation flight control system, control feel, aerodynamic model, displays, sensors, and allows real-time monitoring and recording of test data. Audio and video information (from cameras, displays, and crew voices) is also recorded onboard using digital recorders. The FTE stations are also utilized to monitor and operate any additional sensors, processors, or recording equipment specifically installed for UAV surrogate work.

All of the IFS Learjets additionally operate as ground simulators. The VSS computer is programmed with the equations of motion of the Learjet which drives the sensor system while in the ground simulation mode allowing the VSS to function exactly as it would in flight. The EP has a flat panel display mounted on the instrument panel which presents critical flight parameters in a head-down display format allowing the EP to “fly” the Learjet, albeit lacking the real-world motion and external visual cues. This mode can also be utilized to simulate autonomous flight of UAV systems using the real the UAV hardware installed in the Learjet prior to going to flight test. This ground simulator mode of operation is indispensable for checkout of new configurations, software updates, and familiarizing an EP with the aircraft.

**AUTONOMOUS AERIAL REFUELING**

Removing all humans from an aircraft eliminates the requirement for a UAV to frequently land. Adding aerial refueling capability to UAVs is highly desired so that their range and endurance can be significantly increased. However, there is always an increased level of risk involved whenever two aircraft fly in close formation which is the situation encountered when conducting aerial refueling. Using the Learjet as a manned surrogate allows the development of AAR technology for UAVs to be conducted using a safe build-up approach. As part of these programs, UAV navigation sensors, vision systems, and flight control computers are installed in the Learjet and integrated with the
VSS to provide the UAV system with authority over the Learjet flight controls. In a manned surrogate, refueling approaches can first be flown manually by the pilot while the AAR systems are operating and collecting data. This provides a real world checkout of all sensors and confirmation that the flight control commands are proper prior to the AAR system being used for closed-loop control. During autonomously controlled maneuvers, the SP monitors the Learjet responses and is ready to take control of the aircraft at any point should an unsafe flight condition arise. Calspan's IFS Learjets have been used as UAV surrogates to support the development of AAR capability for both the US Air Force (boom-receptacle) and the US Navy (probe-drogue).

**Air Force AAR**

The Air Force Research Laboratory (AFRL) is developing AAR capabilities as part of its advanced UAV programs. The primary challenge of AAR is obtaining UAV position and orientation relative to the tanker with enough precision to allow the UAV to maneuver and hold position in close formation with the tanker. Various systems are under development for obtaining accurate relative position including systems utilizing precision GPS and hybrid systems incorporating optical systems. To minimize risk before going to an unmanned platform with these systems, the Air Force decided to use Calspan Learjets as surrogate aircraft. AAR systems are onboard and interfaced to the Learjet flight controls through the VSS to assist in the development and evaluate the safety and acceptability of the use of these systems. Several rounds of flights tests have been flown to date to test all aspects of these AAR systems, totaling 170 flight hours in the IFS Learjets. Flight tests have been performed at Niagara Falls, NY; China Lake, CA; Forbes Field – Topeka, KS; and St. Augustine, FL.

The first phase of flight tests, flown in September 2004, cleared the Learjet to operate in the refueling environment around a KC-135 tanker. The Learjet was also used in this phase to gather data with the installed precision GPS and optical sensors to evaluate the ability of the sensors to determine relative position with respect to the tanker in various maneuvers. All of these AAR sensor systems plus the flight control computer hosting the AAR control laws were tested in July-August 2006 to evaluate the closed-loop system which automatically held the Learjet in various refueling formation positions with respect to the tanker, including the contact position (Figure 3). No actual contacts were made during this program since the Learjet was not designed for aerial refueling and does not have a refueling receptacle. This flight test program was also the first to utilize the programmable auto-throttles added to the Learjet VSS. A flight test session flown during July-September 2007 used the previously flown closed-loop control laws but with the addition of trajectory control to autonomously move the Learjet between various refueling formation positions around the tanker, including rendezvous from 3 miles in trail up to contact and then breakaway. The most recent round of flight tests, flown in October-November 2011 and January 2012, evaluated upgraded sensors and improved relative navigation and positioning software being developed for the AAR mission.
Navy AAR

A related AAR program is now being performed for NAVAIR to assist in the development of AAR capability for the Navy Unmanned Combat Aircraft System (N-UCAS) that is under development utilizing Northrop Grumman’s (NGC) X-47B. The X-47B uses the probe and drogue refueling method in addition to the boom and receptacle system used by the Air Force. A Calspan Learjet is being used as the surrogate X-47B and has had the X-47B INS, GPS, optical sensors, and datalinks installed inside its cabin for various flight test programs. Two precursor flight tests were performed for NGC during which the IFS Learjet performed rendezvous and station keeping maneuvers that demonstrated fully autonomous control around a second Learjet acting as a tanker surrogate and later around an actual Omega 707 tanker with its hose and drogue extended (Figure 4). The first flight test session for NAVAIR was performed in October 2010 which collected optical and precision navigation data. Follow-on flight tests were flown in November 2011 through January 2012 that demonstrated fully autonomous control from rendezvous to contact position followed by breakaway. Flight tests have been performed at Niagara Falls, NY; Brunswick, GA; and St. Augustine, FL totaling 162 IFS Learjet hours to date.

Calspan is currently developing and testing a Calspan-designed inert refueling probe (no fuel transferred) that will be installed on an IFS Learjet (Figure 5) to support follow-
on Navy AAR flight activity planned for later in 2013. This will allow the Learjet to make actual plug-in contact with the drogue under both manual and autonomous control.

Figure 5: Learjet with Refueling Probe Installed

SENSE AND AVOID

Just like any manned aircraft, a UAV operating in the National Airspace System (NAS) will need the capability to “see” other aircraft in its vicinity and avoid any potential collisions. An autonomous SAA system will allow UAVs to operate freely in the NAS because the system will provide an “equivalent level of safety” and “equivalent level of behavior” as a manned aircraft regarding the ability to avoid other aircraft if they represent a collision hazard. AFRL and NGC are conducting developmental research with the objective to integrate passive and active systems and provide the ability to sense conflicting air traffic, determine if there is a collision hazard, and autonomously maneuver to avoid midair and near midair collisions. Towards these ends, the SAA flight program has been using an IFS Learjet as a manned surrogate to evaluate visual camera and radar based detection systems to sense “non-cooperative” conflicting air traffic.

Calspan has installed NGC-supplied optical sensors in the nose of the Learjet, a prototype air traffic detection radar external to the fuselage below the nose of the aircraft (Figure 6), as well as the associated SAA processors and data recorders in the aft cabin. The SAA processors are integrated with the Learjet VSS autopilot which is configured to simulate the aircraft dynamics of and respond in a manner similar to the NGC Global Hawk. When an intruder is detected in flight by the SAA sensors, the Learjet VSS receives commands from the SAA system to change course to avoid the detected intruder. Once a safe separation distance has been achieved, control reverts to the Learjet VSS autopilot. The Learjet was flown in various near-collision encounter scenarios with aircraft representative of general aviation and commuter transport category platforms acting as intruder aircraft on a collision course. The intercepting flight profiles included head-on, over-take, and crossing patterns against various “intruder” aircraft including FAA-provided King Air and Convair-580, as well as another Calspan Learjet, Bonanza, and Gulfstream-III aircraft. All flight tests have been performed at Calspan’s Flight Research Facility in Niagara Falls, NY. A total of 228
hours have been flown to date under various phases of this project between 2006 and 2013.

![Figure 6: Learjet with SAA Radar Installed](image)

**REMTOTEILY PIOTED AIRCRAFT**

One of the alternatives to a fully autonomous UAV is to utilize a remotely located, external pilot to complete the takeoff and landings rather than require an automatic takeoff and landing mode. To this end, the Calspan IFS Learjets have been configured as surrogate RPA for various flight test programs. In this configuration, the Learjet is equipped with a radio datalink that allows two-way communication between the Learjet and a ground station. Learjet state information is telemetered from the aircraft to the ground station where it is displayed to the Remote Pilot (RP). Based on this information, the RP moves the ground station controllers whose inputs are telemetered back up to the Learjet where it is interfaced to the Learjet flight controls through the VSS providing the RP with closed-loop control of the aircraft. The Learjet is an ideal safe RPA surrogate because there is still a SP in the aircraft ready to take control at the push of a button should there be a loss of communication with the ground station or if any other unsafe flight condition should arise.

**Fighter Surrogate Risk Reduction**

As part of the Air Force and Navy Fighter Surrogate program, Calspan conducted an IFS Learjet flight test program in 2008 aimed at reducing the risks associated with remotely piloting fighter aircraft. The primary objective of this test was to demonstrate that a RP can land an F-16 like aircraft with an acceptable pilot workload utilizing only the legacy F-16 control laws and a minimal ground station configuration. A secondary objective was to evaluate various pilot relief modes that provide additional augmentation of a single DOF to minimize the compensation required by the RP. The Learjet was chosen because it has safely simulated numerous aircraft in the approach and landing flight phase in previous programs.

An uplink receiver and downlink transmitter was installed in the Learjet to communicate with the ground station installed in the radio room of Calspan’s Flight Research Facility in Niagara Falls, NY. The ground station (Figure 7) consisted of a side stick, pedals, and throttles that were similar to an F-16’s as well as displays showing the actual out-
the-window video from the Learjet camera and computer generated out-the-window scenery with a head-up display (HUD) driven by VSS sensor information downlinked from the Learjet. The stick commands from the RP were uplinked to the Learjet where they were interfaced to the VSS to control the aircraft. The VSS computer was configured to enable the Learjet to replicate the responses of an F-16 to the RP commands.

![Figure 7: Fighter Surrogate Learjet Ground Station](image)

Flight testing was conducted using a build-up approach. Approaches were first flown by the SP inside of the Learjet with the RP monitoring the video and data feeds at the ground station to get familiar with the sight picture and display characteristics. The RP was then given control of the aircraft on downwind to fly a series of low approaches to go-around starting at 100 ft building down to actual touchdown. The test program culminated in the Calspan RP successfully flying the Learjet to touchdown. By the end of the test program, the RP was able to repeatedly fly the Learjet to touchdown using the minimal ground station.

**USAF Test Pilot School Test Management Projects**

The USAF Test Pilot School (TPS) is making an effort to include more UAV and RPA work into their curriculum. The IFS Learjets, which are already a fixture at the school providing flying qualities training to the TPS pilots and engineers, has been configured as a manned RPA surrogate for multiple Test Management Projects (TMP) to develop RPA capabilities for the school.

The first TMP, HAVE RPA, was flown in 2011 and involved the integration of the Learjet VSS autopilot with a Calspan developed ground station pallet that provided the ground station operator an interface to send autopilot commands (heading, altitude, airspeed) to the Learjet. The ground station received Learjet sensor information and presented this to the operator in both head-down display and moving map formats along with datalink timing status information (Figure 8). This pallet was installed in the TPS control room and was interfaced to the Learjet using a radio datalink similar to the one used on the fighter surrogate project. This ground station pallet can optionally be installed in the aft cabin of the Learjet and connected directly to the VSS for demonstration purposes.
The focus of this TMP was on assessing the datalink range performance and characterizing the datalink latency.

![Figure 8: Calspan RPA Ground Station Pallet and Display](image)

A follow-on TMP, HAVE HAL, added pilot-in-the-loop control. The TPS Handling Qualities Ground Simulator (Figure 9) was used as the ground station to facilitate this. Sensor information from the Learjet was downlinked to the simulator and used to generate HUD symbology and synthetic out-the-window imagery. The simulator sticks, pedals, and throttles were uplinked to the Learjet allowing the RP to fly the Learjet. The uplinked stick commands were switched into the VSS in essentially the same place as the EP stick in the cockpit which allowed the RP to fly the Learjet in any of the VSS demonstration configurations available to a pilot seated inside of the aircraft. During this TMP, TPS student pilots were able to fly the Learjet down to low approach but did not make actual touchdowns. Future TMPs are being planned to install an upgraded radio datalink that will also allow the transmission of video from the Learjet with the end goal of flying the Learjet down to touchdown.

![Figure 9: USAF TPS Handling Qualities Ground Simulator](image)

**CONCLUSIONS AND LESSONS LEARNED**

The IFS Learjets have become successful UAV surrogates because they provide an easily programmable interface to a full authority fly-by-wire flight control system and the ability to test developmental UAV systems in a safe environment. The Learjets are
especially valuable in flight regimes with an elevated level of risk (e.g., landing, formation with other aircraft) where testing developmental systems in a fully unmanned aircraft would be unsafe. Using a manned surrogate allows maneuvers to be flown manually prior to being flown autonomously providing a preliminary checkout of UAV system sensors and control laws in a real flight environment before giving the UAV system control of the aircraft. While flying autonomously in the IFS Learjet, the SP is always monitoring the aircraft’s response and is ready to take back manual control with the push of a button in the event of a loss of communication, failure of a system component, inappropriate control input, or if any other unsafe condition develops; all things that are common occurrences on developmental test programs. The VSS ST system provides additional monitoring to back up the pilot and to prevent unsafe inputs from moving the Learjet flight controls.

Though the Learjet is well-suited for the manned UAV surrogate role, it does have some limitations. Some of these programs are approaching the volume and weight limits of equipment that can be installed inside the Learjet cabin. The SAA radar (Figure 6) is also approaching the limit on the size of equipment that can be suspended external to the Learjet. To continue UAV surrogate work and go beyond these limits Calspan has purchased a Gulfstream G-III and modified it into an airborne testbed (Figure 10). The G-III provides an increased capacity to install UAV system equipment and additional FTE workstations within the cabin. The G-III can also house a larger radar within its production radome. Mission durations for the G-III can exceed 7 hours, significantly greater than the Learjet. Calspan has already made several modifications to the G-III system including adding readily available power distribution for new equipment, integrated communication with the G-III aircraft sensors, installation of a MAU-40 bomb ejector rack in a centerline pylon to hold up to 2,000 pounds of external stores, and the installation of a Common System Radome (CSR) on top of the fuselage for the housing of additional sensors. Calspan is currently evaluating several options for autonomously driving the G-III flight controls to provide either a full VSS or VSS-like capability for the aircraft so that it can extend the UAV surrogate work started with the Learjets.
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REFERENCES


BIOGRAPHY

Ryan McMahon is an Associate Program Manager in the Calspan Flight Research Group with more than 8 years’ experience in flight control, modeling of aircraft dynamics, flight testing, systems engineering, and project management. He received his BS in Aerospace Engineering from the University of Notre Dame and his MS in Mechanical Engineering from the State University of New York at Buffalo with a focus on aircraft dynamics and parameter identification. He is the currently the Calspan Project Manager for both the US Air Force’s SAA and NAVAIR’s AAR programs. Mr. McMahon’s primary engineering responsibilities at Calspan include the development and management of flight control software for Calspan’s Variable Stability Learjets and the VISTA F-16. The control laws in these aircraft are utilized for handling qualities training, URT, in-flight simulation research, and as surrogate UAVs. Mr. McMahon frequently serves as an onboard FTE during flight test programs.