

NASA's Learn-to-Fly Project Overview

Eugene H. D. Heim^{*}, Erik M. Viken[†], Jay M. Brandon[‡], and Mark A. Croom[§]
NASA Langley Research Center, Hampton, VA, 23681-2199, United States

Learn-to-Fly (L2F) is an advanced technology development effort aimed at assessing the feasibility of real-time, self-learning flight vehicles. Specifically, research has been conducted on merging real-time aerodynamic modeling, learning adaptive control, and other disciplines with the goal of using this “learn to fly” methodology to replace the current iterative vehicle development paradigm, substantially reducing the typical ground and flight testing requirements for air vehicle design. Recent activities included an aggressive flight test program with unique fully autonomous flight test vehicles to rapidly advance L2F technology. This paper presents an overview of the project and key components.

I. Nomenclature

ARF	=	almost ready to fly
CAS	=	Convergent Aeronautics Solutions
CFD	=	Computational Fluid Dynamics
Cm_α	=	non-dimensional pitch static stability with angle of attack, per deg
FTS	=	flight termination system
GP	=	Generalized Pilot
GPS	=	Global Positioning System
IMU	=	inertial measurement unit
k_α	=	angle of attack control gain
L2F	=	Learn-to-Fly
L/D	=	aerodynamic lift to drag ratio
MOF	=	multivariate orthogonal functions
PTIs	=	Programmed Test Inputs
R/C	=	radio control
TACP	=	Transformative Aeronautics Concepts Program
UAS	=	unmanned aircraft system

II. Introduction

A “Learn-to-Fly” approach is being developed by NASA within the Transformative Aeronautics Concepts Program (TACP) with a goal of changing the paradigm of aircraft development. The conventional process of aircraft development includes a sequential, iterative process of model development from wind tunnel tests and CFD, simulation development, control law development, and finally flight test. Inevitably, during flight test, aerodynamic model updates are found to be required, and the rest of the previous process repeats. Learn-to-Fly (L2F) combines real-time nonlinear aerodynamic modeling with autonomous control law design. These two paradigms are illustrated in Fig. 1. Benefits include aerodynamic models based on flight data used in the control law design – so corrections due to Reynolds number (if flights are full-scale), blockage, boundary-layer turbulence, etc. are not necessary – and control system design is developed with actual flight dynamics responses, rather than simulation results. As the L2F technologies and processes mature, novel aircraft designs may be able to be flown with no ground-based testing. There are three pillars in the L2F philosophy that have been the focus of recent studies: 1) real-time nonlinear aerodynamic modeling; 2) “learning” control law design methods; and 3) guidance algorithms.¹⁻⁷ State of the art flight test aerodynamic modeling approaches were combined with guidance and learning control law design methods onboard

^{*} Research Engineer, Flight Dynamics Branch, Mail Stop 308, Senior Member, AIAA.

[†] Research Engineer, Flight Dynamics Branch, Mail Stop 308, Member, AIAA.

[‡] Senior Research Engineer, Flight Dynamics Branch, Mail Stop 308, Associate Fellow, AIAA.

[§] Senior Research Engineer, Flight Dynamics Branch, Mail Stop 308.

the aircraft in real time and applied in flight during the L2F research. These technologies enable the aircraft to learn how to fly.

Historically, aerodynamic modeling from flight test data has been a multi-step process requiring flight tests followed by post-flight analysis of the data. During post-flight analyses, it is often discovered that insufficient richness in data content exists to develop the desired models, so additional flight testing is required to fill in data gaps. This results in a very time-consuming process that can involve a large number of flight test sorties to acquire the data needed for adequate aerodynamic model development. Recent advances in recursive global nonlinear aerodynamic modeling have enabled this process to be executed in real time onboard the aircraft with little more computing power than a typical laptop.^{1,2} In near real time, the data content in the maneuvers can be assessed while conducting system identification maneuvers that can knowingly continue until a valid aerodynamic model is generated. The ability to produce an aerodynamic model of the vehicle while in flight has opened the potential for autonomously modifying control laws and control allocation schemes, allowing the aircraft to autonomously “learn to fly”, with performance improving as more flight time is experienced.⁷⁻⁹

This paper provides an overview of the Learn-to-Fly research under a recently-concluded TACP/Convergent Aeronautics Solutions (CAS) project. The goal of the CAS Learn-to-Fly project was to prove feasibility of this concept by answering the following question: Is it possible with conventional off-the-shelf computing hardware to merge real-time aerodynamic modeling, real-time guidance, and learning adaptive control; identify the aerodynamics of the aircraft with no a priori aerodynamic knowledge; and then stabilize, control, and navigate the aircraft autonomously?

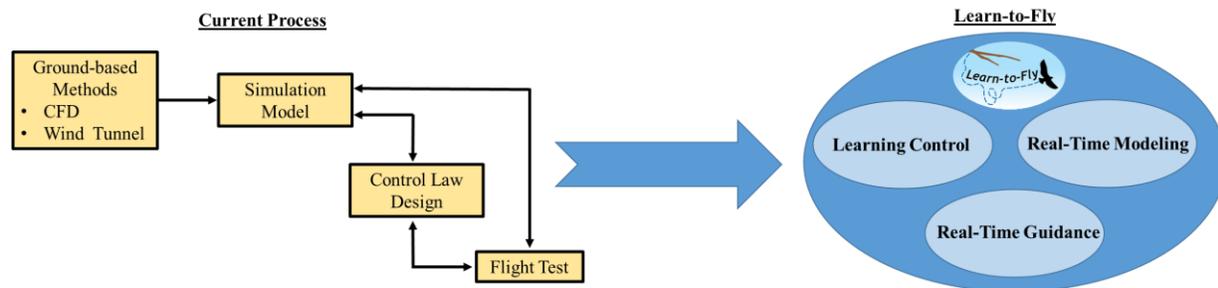


Fig. 1 Conventional aircraft development process vs. Learn-to-Fly concept.

III. Approach

To explore the Learn-to-Fly concept in this CAS effort, aggressive steps were taken to quickly address the crucial question of concept feasibility. A break from the conventional approach was taken right from the start. Flight tests of novel, never-before-flown glider configurations were conducted without the benefit of ground-based aerodynamic testing. The aircraft avionics were designed to autonomously develop and refine aerodynamic models and to autonomously synthesize guidance, navigation, and control laws in flight, updating as it learns more about itself. A conventional powered vehicle was also used during flight testing. A description of the vehicles used during the project is provided in Section A.

Fig. 2 provides a high-level block diagram of the algorithm. Excitation inputs were added to nominal flight control commands. These excitation inputs, or Programmable Test Inputs (PTIs), consisted of optimized orthogonalized multisines and were used to excite the vehicle’s natural dynamic modes. Real-time global aerodynamic modeling was able to attribute vehicle response dynamics due to individual control surfaces and produced an aerodynamic model, including stability and control derivatives and performance parameters. Guidance commands were calculated based on estimated maximum L/D (glider only). The desired dynamics were then updated to reflect the vehicle’s capability based on real-time aerodynamic modeling results. Control commands were then computed based on estimated vehicle dynamics, again from the real-time aerodynamic model. Finally, commands were allocated to surfaces based on estimated control effectiveness. Note that the development of the L2F algorithms did not use aerodynamic data from wind tunnel or CFD codes. Only limited, intentionally low-fidelity vortex lattice data was used for the never-before-flown glider configuration.

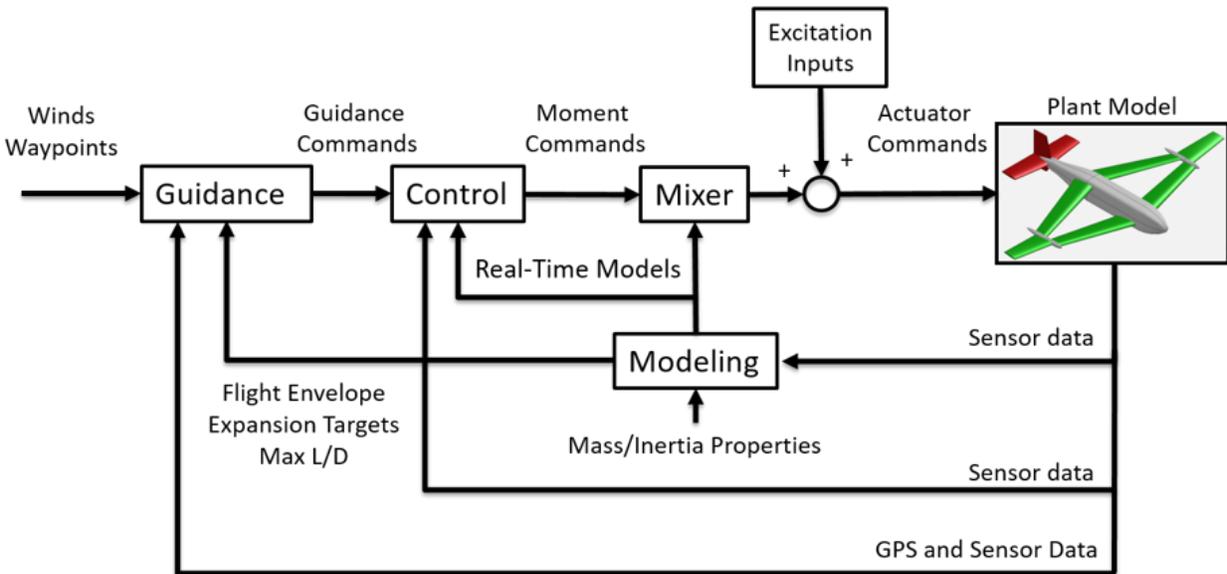


Fig. 2 Block diagram of Learn-to-Fly algorithm.

A. Flight Test Aircraft

The Learn-to-Fly challenge was to fly new aircraft designs with no ground-based aerodynamic testing. Feasibility would be assessed simply by the ability of the algorithms to fly the aircraft. At a high level, the L2F flight tests could be categorized by whether the flight article was unpowered or powered. In an effort to reduce both complexity and costs of flight operations, three of the four airframes, designated as Foamie (Fig. 3), Super Guppy Foamie (Fig. 4), and Woodstock (Fig. 5), were selected to be unpowered gliders that were released from a tethered balloon and possessed only basic landing skids. In contrast, the E1 (Fig. 6) flight testbed was an electric powered, propeller-driven aircraft. Despite their distinct configuration differences, all aircraft were engineered with the capability to fly fully autonomously or under conventional R/C pilot control. The following section briefly describes the flight test aircraft. Further details can be found in Ref. [10].

Initial checkout of the L2F approach was done using the Foamie airframe, a modified MiG-27 Foam Target Drone. Modifications included extended wing tips, enlarged ailerons and elevator, and a suite of prototype L2F avionics. Foamie was used in the early part of the L2F project as an inexpensive test article for the development of the tethered balloon drop test techniques, avionics development, and algorithm development.¹⁰ The vehicle was dropped from various altitudes, up to 400 feet AGL, from a tethered balloon at the North Range of the City Environment for Range Testing of Autonomous Integrated Navigation (CERTAIN) test range at NASA Langley Research Center.



Fig. 3 Foamie glider aircraft used for early L2F concept development.



Fig. 4 Super Guppy Foamie glider used for avionics testing.

Super Guppy Foamie (SGF) was a further modified version of Foamie intended to be a test-bed for the proposed Woodstock avionics system. The fuselage volume was increased to accommodate new avionics and the wings were strengthened with two spars to handle the extra weight of the additional hardware and sensors.

The Woodstock aircraft was a novel joined-wing design with twelve independently-controlled surfaces including a unique all-moving empennage for pitch and yaw control. Unlike the earlier Foamie and SGF vehicles, Woodstock was designed to be part of the “graduation exercise” for the CAS Learn-to-Fly project. The design has redundant control surfaces for each axis and an anticipated high level of aerodynamic interaction effects. A primary design goal was to obfuscate the vehicle’s aerodynamic characteristics so that the control allocations were not obvious, thereby forcing the algorithms to learn how to effectively model the aerodynamics and control the vehicle. Doing so ensured that the human control system designers, using their intuitive conventional flight dynamics knowledge, would not be able to readily tune the flight control system (intentionally or otherwise). Similar to Foamie and Super Guppy Foamie, Woodstock was designed as a glider, but was dropped from an altitude between 2000 ft. and 3000 ft. from a larger tethered balloon at Fort A. P. Hill, Virginia.



Fig. 5 Woodstock gliders.

Moreover, the construction of Woodstock utilized a rapid prototype technique in which the entire aircraft was built in parts from nylon using additive 3-D printing technology. The vehicles were designed to be expendable, as with Foamie. However, it was unknown if the vehicles were stable or if an R/C safety pilot could have a chance of recovering and landing them. Therefore, for the Woodstock flights, the R/C safety pilot’s only requirement was ensure range containment. Due to their relatively fragile construction and lack of landing gear, there was no expectation the

vehicles could be remotely piloted and landed without damage, and therefore it was assumed the vehicle would only operate for one flight.



Fig. 6 E1 aircraft.

A more conventional aircraft was chosen for the powered vehicle research. An R/C Almost Ready to Fly (ARF) 40% scale kit of an Extra 330SC, designated as E1, was selected due to its low cost, availability, performance, and payload capacity. The battery-powered E1 aircraft was propelled by a single electric motor. Among a number of modifications made to the ARF model kit, the flaperons were split to provide conventional flaps and ailerons. Additionally, the elevator was also split to allow independent control of left and right surfaces. The onboard avionics were similar to those used on Woodstock, with the exception of a flight mode which allowed R/C pilot commands to be routed through the L2F computer. This pilot-commanded pass-through flight mode facilitated the injection of PTIs into the R/C pilot's command path, thus allowing aerodynamic modeling to occur while the aircraft was under control of the R/C pilot. The R/C pilot also had the ability to switch the aircraft in and out of a fully autonomous flight mode, under which the controls were handled solely by the L2F computer. A third flight mode, known as the R/C mode, allowed the R/C pilot to bypass the L2F computer completely and fly with conventional R/C avionics.

All surfaces on E1 were programmed to be independently controlled. This capability was exploited to artificially destabilize the aircraft (see Fig. 7). During the destabilization test points, the left elevator was programmed to pitch the aircraft up as angle of attack increased, thus destabilizing the airframe statically in pitch. The flaps were programmed to increase the roll with roll rate, thus giving the aircraft unstable roll damping.

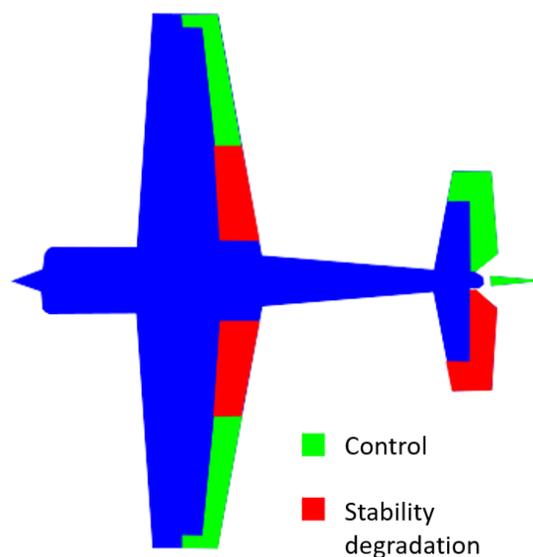


Fig. 7 Control surfaces on E1 aircraft used for stability and control (green) and stability degradation (red).

B. Simulation Development Tools

Simulations of each aircraft were required for algorithm and tool development. Each of these simulations were intentionally low fidelity or even employed surrogate aircraft aerodynamic models. The idea was to provide a capability for algorithm development, but without enough fidelity that the controls and real-time aerodynamic modeling designers could tune their systems a priori. The Foamie and SGF simulations used the aerodynamic model of an F-16 modified from Ref. [11]. The E1 propulsion and aerodynamic models were adapted from the Ultrastick 120 models in Ref. [12, 13]. The Woodstock model was the only simulation that used aerodynamics representative of the actual geometry. However, the aerodynamics were derived from very low-fidelity vortex lattice codes. In all cases, the weight and center of gravity positions of each aircraft were measured.

C. Hardware-In-The-Loop Testing

A mock-up of the avionics system, sans airframe, was assembled for flight hardware and software development. The resulting system was dubbed the “Iron Bird”. The Iron Bird, and the resulting Woodstock and E1 avionics systems, were comprised of a primary flight avionics system, responsible for the R/C pilot control and failsafe modes, and the research avionics system, responsible for the L2F near-real-time modeling and learning control. The primary flight avionics system on both powered and unpowered airframes were Commercial-Off-The-Shelf (COTS) R/C systems while the research avionics systems were a mix of COTS hardware and custom hardware as well as software. Onboard analog sensors included angle of attack and sideslip angle vanes, outside air temperature thermocouple, and a laser altimeter (Woodstock only). Digital sensors consisted of control surface position encoders, absolute and differential pressure transducers, and an inertial measurement unit (IMU). The IMU measured a 3D magnetometer, angular rates and linear accelerations and outputted both attitude and GPS solutions. Furthermore, the research flight control algorithm recorded over 1250 variables at a rate of 50 Hz. These variables included general flight code parameters like flags, raw encoder and analog data, and a timestamp. Other timestamped variables included surface positions, sensor states, guidance and control commands, and internal parameters from the L2F algorithm.

D. Real-Time Global Aerodynamic Modeling

A primary objective of the Learn-to-Fly flight tests was to identify a six-degree-of-freedom mathematical model in real time for each non-dimensional aerodynamic force and moment coefficient during flight over a global, or large range of the flight envelope. Non-dimensional aerodynamic force and moment coefficients cannot be measured directly in flight, but instead must be computed from aircraft measured states, as well as the known geometry and mass properties of the aircraft.⁵ The measured explanatory variables are angle of attack, sideslip angle, non-dimensional body-axis angular rates, and control surface positions. There are two main factors involved in the real-time development of an accurate global aerodynamics model: 1) designing effective and efficient flight maneuvers to sufficiently excite the desired aircraft dynamics across a large flight envelope and 2) the implementation of a real-time, recursive system identification scheme that estimates global models for the aerodynamic forces and moments based on the measured aircraft states and controls.^{5,8}

Orthogonal phase-optimized multisine inputs were injected into the control surface commands during segments of the flight tests.⁵ These PTIs, which have zero-mean and are amplitude limited, facilitate the identification of individual control surface effects, as well as aircraft stability and performance characteristics, in multiple axes at once, while only causing small perturbations from the aircraft nominal flight trajectory.

All of the L2F flight tests employed a real-time global aerodynamic modeling approach using Multivariate Orthogonal Functions (MOF).⁵ The MOF modeling approach begins by generating candidate multivariate functions, known as regressors, based on a nonlinear Taylor series expansion in the explanatory variables, up to a user-defined maximum model complexity, taking into account the available onboard computing capability.^{5,7} These regressors are then orthogonalized using a recursive QR decomposition to isolate, quantify, and rank the explanatory capability unique to each individual modeling term. From there, a least-squares estimator is applied in the form of minimizing the sum of squared differences between the dependent variable measurements and the model. Statistical metrics are used to determine the appropriate regressors to be retained or added to the model. The statistical metrics employed for model structure determination include model fit quality measures as well as a model complexity penalty to reduce the possibility of overfitting, e.g., using a polynomial of too-high a degree. The final steps of the MOF modeling methodology consist of a transformation from the selected orthogonal modeling functions back to physically-meaningful ordinary functions of the explanatory variables, and the calculation of the uncertainties for the associated model parameter estimates. Furthermore, this MOF methodology identifies a separate model for each individual non-dimensional force and moment coefficient, corresponding to minimizing the squared equation error in each individual equation of motion for the six rigid-body degrees of freedom.

E. Real-Time Guidance

The real-time guidance algorithm performed several functions, including waypoint navigation, energy management for autonomous landing, and served as an “executive”, coordinating autonomous envelope expansion and limited envelope protection.⁶ The guidance algorithms used for Woodstock and E1 vehicles were largely the same, with the major exceptions being driven by the differences in their flight operations.

The Woodstock vehicles, being unpowered and balloon launched, required a recovery or pull-up phase. This led to a nominal 1-g gliding phase where the angle of attack and sideslip were systematically varied to expand the flight envelope. Airspeed, angle of attack, and stability parameters computed from the real-time global aerodynamic modeling were monitored for instabilities to provide limited envelope protection. Range navigation was accomplished by computing the ground track to the desired GPS waypoint. Once the vehicle was within a radius of acceptance relative to the waypoint, the commanded ground track would advance to the next preset waypoint. This pattern would repeat until the vehicle descended below a preset altitude and the autonomous landing mode began. At this time the longitudinal command was changed from angle of attack to desired glide-path angle for best L/D. Waypoints for landing were then computed onboard to provide a landing at a predesignated target area and heading.

E1, being powered and proven to be flyable by the safety pilot, allowed for a simpler guidance concept of operations (con-ops). Autonomous landing was not required as the R/C pilot could perform that function. The R/C pilot also performed the takeoff and climb to initial test altitude. The vehicle was flown into various conditions by the R/C pilot, including stalls, and then switched to autonomous mode. The control system then had to recover and track guidance commands to achieve the desired ground track as before with the glider, but the powered guidance included preset altitude and airspeed targets.

F. Learning Control Laws

The primary functions of any control law are to stabilize the vehicle and track guidance commands. Control law architecture can vary widely. This study explored two designs which both were able to utilize the real-time aerodynamic model to stabilize the vehicle and increase guidance command tracking performance. Improvements in stability and tracking were accomplished by the “learning” of the real-time aerodynamic modeling. Learning implies retaining knowledge from past experience in order to influence behavior or performance for future experiences. Both were able to “learn” by taking advantage of the real-time improvements of the aerodynamic model, thus improving the augmentation they themselves were providing. Each architecture utilized linear models derived from the continuously improving and expanding aerodynamic model in order to tune gains to meet predetermined stability metrics or attain predetermined desired dynamics.⁷

The Generalized Pilot (GP) control law design was based on a simple classical control law scheme utilizing angular rate feedback in the inner loop. Outer loops were closed about pitch attitude, sideslip, and ground track. The motivation was to mimic an R/C pilot who controls flight path and attitude rather than angle of attack. Minimizing the dependence of explanatory variables in the control laws may have important implications on the real-time aerodynamic model as explanatory variables that are tracked too well by the control laws become correlated and degrade the ability to identify the aerodynamics. With this in mind, augmentation was limited to the roll mode time constant, short period mode damping, and Dutch roll mode damping.⁷ A disadvantage of this design is that it required some fixed gains and had to have a priori knowledge of the direction (but not amplitude) of the control power terms.

The adaptive nonlinear dynamic inversion controller was a more complex control architecture that depended heavily on the real-time aerodynamic model and required very little to be known a priori about the aerodynamics.⁷ Nonlinear dynamic inversion requires an onboard aerodynamic model to effectively cancel out nonlinearities due to the aerodynamics. The motivation here was to take advantage of the full real-time aerodynamic model and rely on adaptation in times or areas where the real-time aerodynamic model was lacking fidelity. The goal of this controller was to maintain natural frequency and provide adequate damping. Online linear models derived from the real-time aerodynamic model were used to tune inner and outer loop gains. The adaptive disturbance rejection assisted the inner-loop by comparing the response to desired dynamics, again based on the linear models derived from the real-time aerodynamic model. The adaptive nonlinear dynamic inversion controller was capable of providing excellent tracking of guidance commands. Simulations revealed rejecting too much disturbance degraded the real-time aerodynamic modeling’s ability to identify a model. Simulations of the Woodstock aircraft in particular, showed this interaction could lead to adverse control-modeling consequences.⁷ No adverse control-modeling was observed in flight for any aircraft.

G. Flight Test and Balloon Operations

As stated earlier, the L2F flight tests could be categorized by whether the flight article was unpowered or powered. In an effort to reduce both complexity and costs of flight operations, the unpowered tests employed a tethered balloon

system to both position and release the unpowered flight vehicles into their initial test condition. Two different sized aerostats were used throughout the L2F unpowered flight tests: a 1000 ft³ balloon, load rated to 45 pounds, for the Foamie and Super Guppy Foamie tests and a 2000 ft³ balloon, load rated to 90 pounds, for the Woodstock tests (Fig. 8). Despite the significant differences in size and load capacity, the aerostats shared similar structures. Both consisted of a single ply urethane body filled with helium and a fabric sail to help weathervane the balloon. Additionally, both aerostats were equipped with an FAA-approved flight termination system (FTS). In the event of a tether failure, the balloon operator could energize the flight termination system via R/C command to apply current to a wire which would melt a hole in the balloon to allow the helium to escape. A specialized carrier apparatus was mounted below the aerostat, which secured the flight vehicles to the balloon system and hosted the airplane release mechanism. The balloon system was tethered to a trailer via a high-speed winch, which allowed the balloon-plus-airplane assembly to be raised and lowered to the desired initial test condition. Additionally, a vehicle-specific cradle was mounted to the trailer, which allowed the balloon to be securely captured between test runs while keeping it inflated.

Flight tests were split between two test ranges: the North Range of NASA Langley Research Center's CERTAIN test range and Finnegan Field at Fort A.P. Hill. Since the focus of the Foamie and Super Guppy Foamie tests were on the balloon operations and avionics checkouts, the tests were conducted locally at NASA LaRC.¹⁰ In contrast, the Woodstock and E1 flight tests required more altitude, as well as more land area, to operate and, therefore, were conducted at Fort A.P. Hill.



Fig. 8 Aerostat balloon supporting Woodstock with tether highlighted and wind direction indicated.

The general operations surrounding unpowered flight tests adhered to the following process once the balloon was inflated and secured at the test location. First, the L2F team would perform a glider preflight checkout including confirmation of successful control surface inputs and air data measurement readings. The glider would then be attached to the carrier release mechanism. At that point the Range Safety Officer would contact the range office and await flight authorization. Once authorized, the team would then arm the balloon burn down unit and winch the flight article to the predetermined flight initiation altitude. When the flight vehicle and balloon system reached a steady initial condition, an R/C command was sent to energize the glider release mechanism. The glider would then perform a pull-out maneuver and follow the user-designated flight path, all while the learning algorithms were active. Each flight was planned to end with the glider performing a flare maneuver and touchdown at the specified landing location.

At any time throughout the flight test, the safety pilot could assume R/C control of the vehicle if confronted with a safety issue, range boundary violation, or system failure.

As mentioned earlier, a key factor in the powered flight tests was the ability to switch between three different flight modes: safety mode, pilot commanded pass-through mode, and full autonomy mode. Selection of the flight mode was made via a toggle switch on the safety pilot's R/C transmitter. As with the unpowered testing, powered tests started with a preflight checkout and flight authorization. From there, aircraft would perform the takeoff in the safety flight mode under R/C control of the external safety pilot. Upon reaching the initial test condition, the safety pilot would activate either of the two research flight modes: pilot commanded pass-through or full autonomy mode. The L2F powered flight tests involved a developmental autopilot study and a variable stability study, both are detailed in the accompanying Learn-to-Fly Test Setup and Concept of Operations paper, Ref. [10]. Flight time was carefully monitored throughout the powered tests and once the margined battery capacity was reached, the safety pilot would assume control, via the safety flight mode, to land the aircraft.

Following both powered and unpowered flight test runs, flight data was uploaded to the test engineer's computer from the aircraft and distributed among the L2F engineers for data analysis and algorithm enhancements.

IV. Flight Test Results and Discussion

Feasibility of the Learn-to-Fly concept was judged by the algorithms' ability to fly the aircraft, and only one successful flight was required to prove feasibility. The Foamie flights provided a good indication that the concept was feasible, since a few flights were highly successful. Winds during these flights were relatively calm, which reduced the impact of not having air data (airspeed, angle of attack, and sideslip). Flights with significant winds were not successful, and the safety pilot had to intervene to recover the aircraft from departed flight conditions. Another limitation was that the Foamie aircraft was a conventional stable design that was known to be flyable by an R/C pilot. Recall the L2F challenge was to fly new aircraft designs without relying on ground-based aerodynamic testing.

Due to the increased weight of SGF, the tethered balloon was only able to achieve an altitude of 250 feet, which was insufficient altitude for the systems to establish flight. Only systems-performance insights, not L2F feasibility assessments, were gleaned from the SGF flight, which ended in loss of the vehicle. However, the findings from SGF proved valuable as they informed the ensuing approaches in what was very likely the most expeditious and cost-effective manner. This approach incurred minimal lost programmatic time at the risk and loss of an insignificantly valued asset. Data corruption led to an inoperable vehicle upon drop from the tethered balloon. The safety pilot attempted to recover the aircraft manually with R/C control but was unable to do so during the six-second flight. Although Super Guppy Foamie's only flight was not successful, data from the balloon ascent was useful in verifying the new avionics, and refinements to the approaches intended for the more valuable assets were quickly uncovered, thus making the mission valuable to the project.

The Woodstock vehicles were novel designs, and no ground based aerodynamic testing (wind tunnel or high fidelity CFD) were available. It was unknown whether these vehicles could fly or not, and these were meant to serve as the definitive test of feasibility of the concept. Unfortunately, other factors outside of the Learn-to-Fly research questions prevented the successful testing of these aircraft. The first Woodstock was lost due to its vertical tail impacting the support structure on the balloon. The impact stripped the elevator control servo arm splines and rendered the elevator semi-free to float. Immediately after release from the balloon the aircraft nosed inverted and entered a slow stable inverted spiral at an angle of attack of -38 degrees. Limits on allowable roll error in the control laws prevented the control system from correcting the roll error and returning the vehicle upright. Real-time global aerodynamic modeling performed as intended and an aerodynamic model at -38 degree alpha was obtained, although it was of academic interest only and not particularly useful to the project.

The team reevaluated the control error limits and modified the control laws to avoid a similar scenario with the second Woodstock. The modified control laws were then tested on E1 prior to flying the second Woodstock vehicle. E1 was flown to altitude under normal R/C control and put into a condition similar to a balloon drop. Throttle was then set to idle and the aircraft flew as a glider autonomously as intended during the up-and-away flight segment. Once established on final approach, the R/C pilot took control for the landing. Landing was not deemed a necessary aspect to demonstrate at this point in the L2F research, as it needlessly increased risk of damaging the vehicle.

The second Woodstock was launched from the balloon and performed a pull-up to controlled wings-level flight. This portion of the control laws used a simple fixed-gain rate-feedback control law which was set to run for the first four seconds after drop. Real-time global aerodynamic modeling data was acquired two seconds after drop. The first models were output to the control laws at four seconds. Also, at four seconds the control laws were switched from the simple pull-up controls to the adaptive nonlinear dynamic inversion research control law, and guidance tracking was initiated. The aircraft entered a bank to turn towards the first waypoint. Shortly thereafter, sideslip built up

rapidly to 30 degrees and the aircraft then pitched up, stalled, and entered a series of spins. The vehicle was ultimately unrecoverable by the safety pilot and crashed.

E1 was flown with slightly different objectives than the gliders. Since the vehicle was powered, it could maintain altitude and speed. The vehicle was flown several times, with different learning- and adapting-control laws. As built, E1 is a stable aircraft. The team took advantage of the independently controlled and programmable control surfaces to artificially make the aircraft unstable. The vehicle was flown both under R/C pilot control and under full autonomous control while being artificially destabilized statically in pitch and dynamically in roll. Fig. 9 shows the comparison of a flight with large static pitch instability. The real-time global aerodynamic modeling results were used post flight to estimate that the static margin was -16.4%, a significant instability. As shown in Fig. 9 the R/C pilot was unable to maintain pitch attitude and was saturating the elevator while attempting to do so. The L2F algorithm was initialized with a guess of a stable aircraft, as shown in the C_{m_α} time-history. The modeling was able to identify the pitch instability in less than two seconds. The learning control laws then adjusted the control gain k_α accordingly. Elevator control activity was high, but the attitude, altitude, and speed (not shown) were also maintained. It should be noted the R/C pilot time-history is much shorter because the pilot did not want to attempt to fly into a turn in the unstable configuration. However, the L2F algorithm flew through the same turn as well as a second turn before the experiment was concluded.

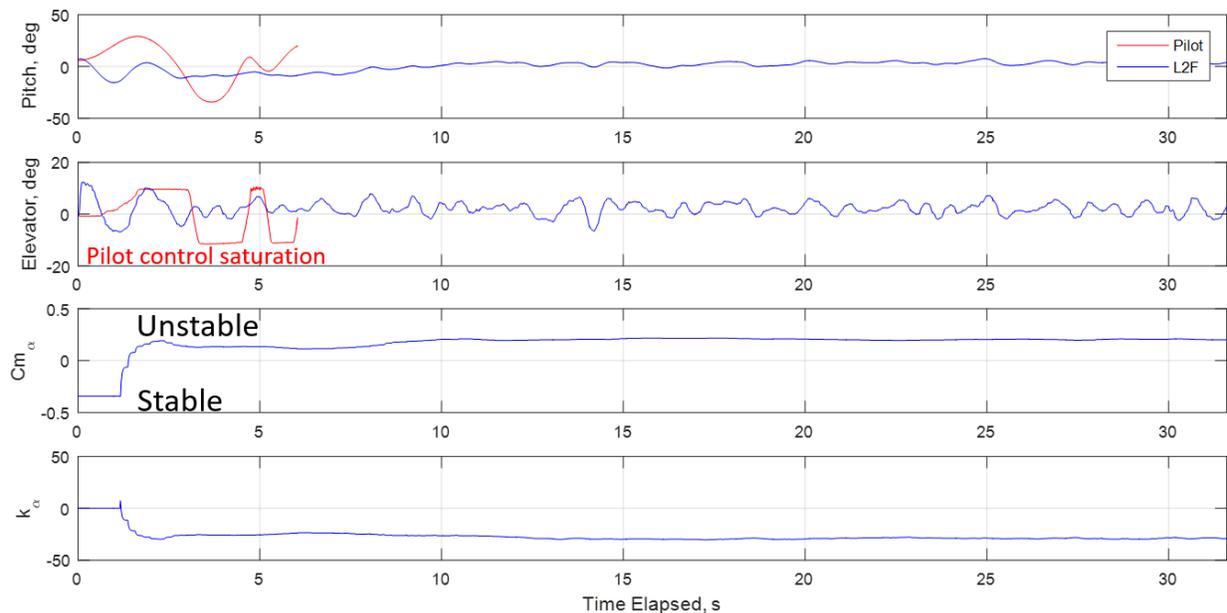


Fig. 9 Time-histories of pitch attitude (top), elevator position (second from top), real-time derived C_{m_α} (third from top), and derived control gain k_α (bottom) for E1 flights with degraded static longitudinal stability, R/C piloted (red) and autonomous (blue).

V. Conclusions

The Learn-to-Fly concept was flown on an aircraft in both stable and unstable configurations without any prior knowledge of the aerodynamics of the vehicle. It was shown that real-time global aerodynamic modeling, adaptive learning control, and real-time guidance can be implemented onboard an aircraft operating at 50 Hz with current, low-end computing hardware. Programmed Test Inputs were successful in producing good dynamic data for real-time modeling. Real-time modeling was shown to reasonably identify linear aerodynamic dependencies in less than two seconds, and automated real-time onboard global nonlinear aerodynamic modeling was demonstrated in flight. Real-time guidance was able to use energy management to meet performance goals. Learning control laws were able to adjust the desired dynamics based on learned vehicle capabilities, and control commands were computed based on estimated vehicle dynamics and control effectiveness.

The tethered balloon launch system was not a primary area of the Learn-to-Fly research, but it was a critical capability development area which enabled rapid and inexpensive flight testing of the core L2F technologies with

unpowered gliding aircraft. The gliders were both aerodynamically and operationally much simpler to operate than powered vehicles. This simplicity enabled an aggressive flight test campaign philosophy of “test early and test often”, particularly with the Foamie aircraft. The Foamie aircraft being inexpensive, expendable, and known to be flyable via R/C safety pilot enabled this rapid flight testing philosophy. Far less time was spent on verification of flight software than a typical flight test program. Actual flights were used to identify deficiencies in the L2F algorithms in lieu of countless hours of simulations, proving real-life relevant feedback to the design engineers.

The tethered balloon system and gliders did not come without costs. The balloon required support equipment, not to mention a supply of helium and associated bottles.¹⁰ Additionally, it required a tether, which in turn forced the initial conditions of the glider launch to be well above an angle of attack of 90 deg. This condition often caused the Foamie aircraft to weathervane longitudinally and tuck under during release. The balloon also has weight limits for a required altitude. The SGF flights highlighted this fact by missing the desired release altitude of 400 ft. by 150 ft. This did not allow enough altitude for the R/C safety pilot to be able to recover the vehicle. The initial drop location is also not completely controllable as winds at altitude will cause the balloon to drift from the winch location. The drift can be particularly exacerbated at higher altitudes. Also, with higher altitudes, the line-of-sight visibility of the aircraft is reduced, thus diminishing the R/C safety pilot’s ability to fly the aircraft. The R/C safety pilot requires direct line-of-sight, which in turn limits the launch altitude, primarily due to range safety concerns. This could be alleviated by telemetering an airframe nose camera view to provide the safety pilot the ability to determine attitude and fly the vehicle from much farther away, at the increased cost of complexity.¹⁰ Finally, there are limited test sites suitable/available for balloon or high-altitude UAS operations.

The Woodstock flight tests unfortunately did not yield any significant data to prove the feasibility of the Learn-to-Fly concept. While parts of the concept performed as expected during these flights, the system as a whole did not have the opportunity to show the vehicle “learned to fly”, i.e. stabilize, control, and navigate. However, the Woodstock flights did provide valuable insight into applying the L2F concept to novel configurations where nothing, or very little, is known about the vehicle’s flight dynamics. In particular, the real-time aerodynamic modeling results necessarily have a slight time lag. The aircraft dynamic modes must be excited and exhibited in the data before the aerodynamics can be identified. A robust stabilizing control law must prevent the aircraft from departing controlled flight for the first few seconds, to allow enough time to identify an accurate model for precise control. Such a controller would enable a more sequential phased approach such as to stabilize first, learn, and then track performance goals.

The E1 aircraft, with the inherent ability to be reliably flown to test conditions and returned for landing, provided an excellent platform for feasibility assessment. This aircraft was used to validate two different learning control laws, as shown in Ref. [7], real-time aerodynamic modeling, as shown in Ref. [5], and real-time guidance, as shown in Ref [6]. Additionally, it validated the L2F concept for gliding flight and autonomous landing, up to the final approach leg.

The goal of the CAS Learn-to-Fly project was to prove feasibility by answering the question, is it possible with conventional off-the-shelf computing hardware to merge real-time aerodynamic modeling, real-time guidance, and learning adapting control; identify the aerodynamics of the aircraft with no a priori aerodynamic knowledge; and then stabilize, control and navigate the aircraft autonomously? The E1 flight tests, specifically the destabilized E1 flights, definitively proved the Learn-to-Fly concept is feasible.

Acknowledgments

This material is based upon work funded by the NASA Aeronautics Research Mission Directorate (ARMD) Convergent Aeronautics Solutions (CAS) project within the broader Transformative Aeronautics Concepts Program (TACP). The authors would like to thank the Learn-to-Fly test team for their hard work and dedication to this project and the Fort A.P. Hill staff for test range access and the excellent support from many individuals.

References

- [1] Brandon, J. M. and Morelli, E. A., “Real-Time Global Nonlinear Aerodynamic Modeling from Flight Data,” *Journal of Aircraft*, Vol. 53, No. 5 (2016), pp. 1261-1297.
doi: 10.2514/1.C033133
- [2] Morelli, E. A., “Real-Time Global Nonlinear Aerodynamic Modeling for Learn-to-Fly,” AIAA Atmospheric Flight Mechanics Conference, AIAA SciTech Forum, (AIAA 2016-2010).
doi: 10.2514/6.2016-2010
- [3] Morelli, E. A., “Flight Test Maneuvers for Efficient Aerodynamic Modeling,” *Journal of Aircraft*, Vol. 49, No. 6 (2012), pp. 1857-1867.
doi: 10.2514/1.C031699

- [4] Morelli, E.A. "Efficient Global Aerodynamic Modeling from Flight Data," AIAA-2012-1050, 50th AIAA Aerospace Sciences Meeting, Nashville, TN, January 2012.
- [5] Morelli, E. A., "Practical Aspects of Real-Time Modeling for the Learn-to-Fly Concept," AIAA Atmospheric Flight Mechanics Conference, AIAA Aviation Forum, June, 2018 (to be published).
- [6] Foster, J. V., "Autonomous Guidance Algorithms for NASA Learn-to-Fly Technology Development," AIAA Atmospheric Flight Mechanics Conference, AIAA Aviation Forum, June, 2018 (to be published).
- [7] Snyder, S. M., Bacon, B. J., Morelli, E. A., Frost, S. A., Teubert, C. A., and Okolo, W. A., "Online Control Design for Learn-to-Fly," AIAA Atmospheric Flight Mechanics Conference, AIAA Aviation Forum, June, 2018 (to be published).
- [8] Weinstein, R., Hubbard, J. E., and Cunningham, M. A., "Fuzzy Modeling and Parallel Distributed Compensation for Aircraft Flight Control from Simulated Flight Data," AIAA Atmospheric Flight Mechanics Conference, AIAA Aviation Forum, June, 2018 (to be published).
- [9] Grauer, J. A., "A Learn-to-Fly Approach for Adaptively Tuning Flight Control Systems," AIAA Atmospheric Flight Mechanics Conference, AIAA Aviation Forum, June, 2018 (to be published).
- [10] Riddick, S. E., Busan, R. C., Cox, D. E., and Laughter, S. A., "Learn-to-Fly Test Setup and Concept of Operations," AIAA Atmospheric Flight Mechanics Conference, AIAA Aviation Forum, June, 2018 (to be published).
- [11] Garza, F. R. and Morelli, E.A., "A Collection of Nonlinear Aircraft Simulations in MATLAB," NASA TM-212145, 2003.
- [12] Owens, B., Cox, D., and Morelli, E., "Development of a Low-Cost Sub-Scale Aircraft for Flight Research: The FASER Project," 25th AIAA Aerodynamic Measurement Technology and Ground Testing Conference, June 2006, 2006-3306. doi: 10.2514/6.2006-3306
- [13] Taylor, B. (2014). Aircraft Simulation Baseline 2014 v1. Retrieved from the University of Minnesota Digital Conservancy, <http://hdl.handle.net/11299/163869>.