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EZ-Fly Prime Concept Demonstrator Flown on Variable Stability Navion

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16. Abstract

The EZ-Fly system was installed on a Ryan Navion. It imported lessons learned from the NASA Langley simulation and AGATE Bonanza flight tests of the EZ-Fly system. The resulting system is called EZ-Fly Prime. Evaluation pilots were typically non-pilots with varying levels of comfort flying an airplane. This project developed a display and navigation system that is optimized for the EZ-Fly Prime flight control system concept for climb, cruise and descent. It includes the ability to easily comply with ATC altitude, heading and speed changes during these phases of flight, and also allows for direct pilot control of the airplane's flight path with integrated envelope protections. As a result of the flight tests, a set of recommendations for 14 CFR 23 amendment 64 means of compliance was developed.

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Acronyms

Acronym	**Definition**
AGATE	Advanced General Aviation Transportation Experiment
AOA	Angle of Attack
ATC	Air Traffic Control
CCD VNAV	Climb, Cruise, Descent, Vertical Navigation
EAA	Experimental Aircraft Association
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FBW	Fly-by-Wire
FMS	Flight Management System
G	Acceleration of gravity
GAMA	General Aviation Manufacturers Association
GCAS	Ground Collision Avoidance System
GPS	Global Positioning System
HITS	Highway In The Sky
HUD	Heads-Up Display
IFR	Instrument Flight Rules
Kt	Knots
MFD	Multi-Function Display
Mmo	Maximum normal operating Mach
MOC	Means Of Compliance
NASA	National Aeronautics and Space Administration
NAV	Navigation
NDB	Non-Directional Beacon
PFD	Primary Flight Display
SVO	Simplified vehicle operations
TAWS	Terrain Alert And Warning System
Vfe	Maximum flap speed
VFR	Visual Flight Rules
Vmo	Maximum normal operating speed
Vne	Never exceed speed
VOR	VHF Omni-directional Range

Acronym	**Definition**
Vref	Approach speed
VTOL	Vertical Takeoff and Landing
Vx	Maximum climb angle speed

Executive summary

A Ryan Navion was modified to contain the EZ-Fly Prime flight control system, which was an improvement on the EZ-Fly system that was flight-tested in a Beechcraft Bonanza. The EZ-Fly system in the Bonanza was an implementation of the original EZ-Fly system developed at NASA Langley. This system targeted the use of Fly-By-Wire technology and computer graphics to improve safety, reduce pilot workload, and reduce the training burden for general aviation airplanes.

The Navion implementation went considerably further than the previous two EZ-Fly developments. EZ-Fly Prime also developed an integrated display and navigation system optimized for the EZ-Fly concept. In doing so, it simplified the human interface for an automated navigation system capable of controlling climbs, descents, cruise, assigned headings, altitudes and airspeeds while reducing or eliminating mode confusion. This was done in a way that the pilot naturally interacts with the automation, instead of turning it on or off and selecting a mode of operation.

As a result of flight testing, existing 14 CFR 23 amendment 64 rules that need to be modified to properly regulate an EZ-Fly Prime system were identified. Furthermore, recommendations for a means of compliance were made.

1 Introduction

While it is possible to certify a Fly-by-Wire (FBW) aircraft under the current certification rules, these rules assume that the FBW aircraft will have handling characteristics like those of mechanically controlled aircraft. There have been several FAR 25 aircraft certified with FBW control systems and they all have handling qualities like their mechanically controlled counterparts. So far, there have not been any FAR 23 FBW aircraft certified.

The EZ-Fly concept was developed to dramatically reduce pilot workload, and it departs from the handling qualities paradigms exemplified by mechanical controls. The purpose of this project was to develop the EZ-Fly concept to the point where it could be used as a model for developing new FAR 23 Means of Compliance (MOCs). The EZ-Fly Prime concept takes advantage of workload reductions, safety features, and potential training reductions that FBW can offer.

1.1 Purpose of EZ-Fly Prime (2018-2019)

The NASA Langley study (Appendix A) was intended to show the potential for reduction in workload, reduction in training, and safety benefits that could be realized by changing from the mechanical controls developed during World War I, and mechanical instrument displays developed in World War II, to concepts that could be realized using FBW and computer-generated graphics. At that time, there was no intent to address certification issues or other barriers to bringing these concepts to market.

NASA Langley and various industry partners jointly funded the Advanced General Aviation Transportation Experiment (AGATE) program. The AGATE Bonanza was developed, owned and operated by Raytheon Aircraft Company (Beechcraft). The company was interested in what it would take to bring the technology demonstrated in the airplane to market. It was determined that this technology could not be certified under the current rules and therefore could not be produced and marketed. The Federal Aviation Administration (FAA) asked for a list of rules that prevented such technology from being certified, as well as what new rules would be appropriate for the new technology. These lists were provided to the FAA shortly before the AGATE program ended.

In the 2010s, FBW was common in FAR 25 aircraft; however, these aircraft mimicked mechanical control strategies using sensors, computers and actuators, and duplicated the mechanical primary flight instrumentation using computer-generated graphics. Thus, the workload reduction, training reduction, and safety aspects of FBW and computer-generated displays were not realized – especially in general aviation where it is needed most. This is proven in general aviation accident rates, which are significantly higher than air carrier accident rates.

EZ-Fly Prime was developed in response to the FAA's recognition that general aviation (especially FAR 23) needs a certification path to FBW. The FAA also desired to improve safety, while simultaneously reducing training and proficiency requirements. In addition, the emergence of the Urban Air Mobility designs require FBW means of compliance for this class of aircraft. The FAA determined that the time was right to develop a set of rules for general aviation FBW that would take advantage of the benefits made available with FBW and computer-generated graphics. It was determined that a flying testbed was needed to develop and test certification means of compliance concepts.

The task was to start with the flight control system from the AGATE Bonanza and install it on a variable stability Navion. Then develop improvements in the flight control system, displays, and human machine interface through ground simulation studies and flight test.

Control, display and navigation systems

EZ-Fly Prime at the time of this writing is the Bonanza system with the following upgrades:

1) The control, display, and navigation systems are integrated into a single interrelated system.
2) The display system is completely different from the current synthetic vision of today's aircraft. Currently certified synthetic vision systems have attitude, airspeed, altitude, heading and attitude guidance as primary display features as required by the FARs.
3) There is a pilot-controlled longitudinal locking mechanism that holds the stick in position for long climbs and descents. This locking mechanism is disengaged when it is overpowered by the pilot or if the pilot depresses an unlock button.
4) The envelope protections are all prioritized and integrated with each other to provide smooth operation in all flight attitudes, including at the limits.
5) This system is designed with the assumption that normal operations will be through a flight plan, with the pilot taking control of the flight path as an exception rather than the rule. As such, this system has the functional features of a fully coupled CCD VNAV (climb, cruise, descent, vertical navigation) system with an auto throttle. Therefore, the system is a steppingstone to fully autonomous operations.

1.2 Navion configuration

The aircraft used was a variable stability Ryan Navion fitted with a hydraulic system that can drive the ailerons, elevator, rudder, flaps (both up and down) and the throttle. All hydraulic actuators are computer controlled. The left cockpit position has an active stick and rudder pedals with an additional three hydraulic actuators, which are also computer controlled. The right cockpit position retains the standard reversible mechanical controls (see Figure 1). When the hydraulic system is disengaged, the hydraulic actuators move freely.

There are multiple buttons placed strategically around the cockpit to facilitate disconnecting the hydraulic system quickly if needed. There are also safety switches connected to aircraft sensors that will disengage the hydraulic system if limits are exceeded. There are approximately 15 additional automatic safety trips.

The safety of the system is maintained through hardware disconnects. The control system software is never used for safety purposes. For the purpose of a safety analysis, the software is assumed to fail in the worst possible way at the worst possible time. The hardware is then the mitigation for the software failure. This allows the use of control software that is not certified to any design assurance level. This concept allows for rapid software changes.

Figure 1. Navion and cockpit

2 EZ-Fly Prime control system

The EZ-Fly Prime control system was developed directly from the AGATE Bonanza control system, but incorporated lessons learned from the AGATE Bonanza and suggestions provided by the FAA. Major improvements include the integration of protections such that they operate seamlessly with commands in a natural and prioritized manner, and a longitudinal stick lock mechanism for long climbs and descents.

2.1 Brief discussion of the improvements from the AGATE Bonanza

2.1.1 Seamless protections

The AGATE Bonanza had bank, G, overspeed and Angle of Attack (AOA) protections. Some of the protections in the Bonanza behaved more like add-ons than an integrated solution. This philosophy is consistent with stick pusher protection in today's certified aircraft. With this kind of protection, the controls provide a discontinuity as they take over the protection function and then give control back to the pilot when safely back inside the desired envelope. While this type of protection ensures safe operation, it can be confusing and disconcerting to the pilot – especially if the pilot is not trained with this device, or has not experienced its operation in training. For the Navion, it was determined that smooth and seamless protections should be incorporated. The Bonanza experience showed that that this was important for novice pilots. Novice pilots grasped that the system kept them safe but then continued to command the aircraft outside of the envelope in order to gain maximum performance. This resulted in the protections turning on and off, which resulted in a safe but erratic flightpath.

2.1.2 Longitudinal stick lock

The AGATE Bonanza flew from Wichita Kansas to Langley Air Force Base in Virginia many times. It also flew to Oshkosh Wisconsin for the Experimental Aircraft Association (EAA) convention and to Kissimmee Florida for the Sun-n-Fun fly in. The EZ-Fly system was used extensively during these trips. These long cross-country trips demonstrated the need to eliminate the requirement that the pilot continually provide a stick force to the stick to maintain long climbs and descents. However, flights with non-pilots also demonstrated the value of having the stick spring loaded to level flight; if the pilot ever got confused, disoriented or uncomfortable, they could simply let go of the stick and the airplane would return to straight and level flight.

The requirements conflict was solved by programming a button on the stick that would hold the stick in its current position with a force that can easily be over-ridden. Pressing the button while the stick is not near the centered position locks it in its current position longitudinally. When the stick is locked to a position, pressing the same button unlocks the stick such that it is spring loaded to center (level flight). Also, if the stick is moved while in a locked position, it unlocks and is spring loaded to the center (level flight) position. Thus, if the pilot gets confused, disoriented or uncomfortable, they only need to move the stick then let go to cause the airplane to go to straight and level flight.

There were many design iterations tested in simulation before the final design described above was chosen. Some of these included changing the spring center when the button was pressed, using a "trim switch" to change the center location, and several versions of button press logic. The ability to try these various concepts quickly demonstrated the value in having an active stick. The active stick allowed rapid changes to inceptor characteristics in software instead of changing hardware.

2.1.3 Lateral stick lock

As the longitudinal stick lock was developed, developing a lateral stick lock was debated. The strongest proponents of a lateral stick lock were the experienced pilots used to an airplane that continues a turn with no lateral control force and the inceptor centered. They brought up the fact that in a hold the stick would have to be held against the spring for about a minute given a standard rate turn.

Opposing a stick lock was the observation that no other vehicle (car, boat, motorcycle, etc.) holds a turn without operator input, and therefore, a lock is not consistent with non-pilot turning experiences and is therefore not intuitive.

Also, the argument concerning a holding pattern was eventually considered non-persuasive because holding for general aviation outside of training is rare and, given the integration of the navigation system, it was conceded that most holds would be done automatically – coupled to a flight plan.

A third argument against providing a lateral lock is the complication of the human machine interface and resulting potential confusion in the presence of a longitudinal lock. Should the lateral and longitudinal locks be coupled such that if one is locked, it locks the other too? If not, there need to be two independent buttons. If there are two independent buttons that do similar things, is there a potential for automation confusion between buttons?

A major goal of the EZ-Fly system is to simplify flight operations and bring highly automated functionality to an aircraft that can be safely operated by pilots with significantly less training than is required today. It was recognized that the benefit of a lateral control lock is limited to relatively rare instances. Since the benefit is relatively small, compared to the potential confusion, it was decided that a lateral control lock did not buy its way onto the EZ-Fly concept.

2.2 EZ-Fly Prime control system description for normal operations

1) Fore and aft motion of the stick commands a vertical flight path angle. The center position commands zero flight path angle (altitude hold). The stick is spring loaded to the center position. The current implementation is air mass referenced, but it is recommended that this be earth referenced when not centered (centered tracks barometric pressure altitude). The reason for earth referenced during climbs and descents is that the pilot can put the flight path marker on a synthetic vision feature and the aircraft will track to it. The reason for barometric altitude while centered is that Air Traffic Control (ATC) expects aircraft to hold barometric altitude when given a clearance.
    a. There is a button on the side of the stick that is used to lock the stick in the current position. It is expected that a production version of this system would have a friction clamp that engages to hold the stick. Pressing the button locks the stick in that position, pressing it when the stick is locked releases the stick. Overpowering the lock releases the lock. This overpower feature allows the pilot to move the stick and then let go which will command the aircraft to fly straight and level.
2) Lateral stick position commands turn rate. This command is scaled such that when the maximum turn rate commands the maximum bank angle, the stick transitions to commanding bank angle. Also, as AOA increases, the stick command is scaled to protect against bank angles that would produce a stall in level flight.
3) There is a speed command lever that is marked in knots of indicated airspeed. After flying this, it has been determined that a better implementation for manual speed control would be to use a knob or wheel that has no stops. Software will limit the commanded speed as appropriate for the current flight condition. This implementation is similar to that used for manually setting the desired airspeed in airplanes that have an auto throttle.
4) There is no manual rudder input. The rudder is controlled exclusively through software to damp Dutch roll, coordinate turns, and counter engine torque and propeller P-Factor.

2.3 EZ-Fly Prime control system flight envelope protections

The philosophy used in determining which protections should be included is that the airplane should protect itself from pilot inputs that have historically been identified as a significant cause of fatal accidents. Loss of control and controlled flight into terrain have been the most common causes of fatal accidents in general aviation. This project does not include takeoff or landing, so protections during the takeoff and landing phases of flight are not considered in this project.

Departing controlled flight often occurs as a result of a stall or pilot disorientation. A stall only occurs at high angle of attack, so angle of attack protection was chosen as one of the required protections. Disorientation often results in the aircraft banking to an excessive degree and then diving to a speed past its structural limit, or the pilot trying to pull out of a dive at high speed and exceeding the structural limits. Excessive pitch and/or bank are the root causes of structural exceedances. However, it is desirable that the airplane be maneuverable. If aggressive pitch and bank protections are enforced, then the maneuverability suffers unacceptably. Therefore, pitch and bank limits are enforced that allow aggressive maneuvering are allowed while AOA, speed and G limits are used to prevent structural or aerodynamic exceedances.

Attitude limits

Bank limits are set between 45 degrees and 60 degrees depending on the airplane and its intended operations. Pitch limits are set to about 15 degrees and may vary up and down depending on the aircraft performance capabilities and its intended operations.

These limits are enough to cause disorientation for many people. However, these limits are only approached while manually maneuvering when the pilot is explicitly commanding these attitudes. The stick is spring loaded to the centered position, which commands straight and level flight. Thus, if the pilot is disoriented while commanding highly dynamic maneuvers near these attitude limits, they can simply let go of the stick and the airplane will immediately go to straight and level flight. This characteristic has proved to be extremely valuable with non-pilots who very quickly build confidence to maneuver up to these limits without previous training.

Structural limits

These attitudes will also allow the airplane to exceed its structural limits. Therefore, G and high-speed limits were also enforced. The G limit is set at about 2 Gs and the high-speed limit is set at the airspeed limit for the current configuration and flight condition (Vfe, Vne, Vmo, Mmo, etc.). The maximum commandable speed is a couple of knots below the structural limit. This allows the controls to produce mild control changes at the commandable limit and more aggressive changes when at the structural limit.

Low-speed limits

Getting too slow on approach and then being upset by a gust can cause a stall and loss of control. It is generally considered safe to fly at 1.3 times the stall speed, and Vref is typically set at 1.3 times stall speed for general aviation airplanes. To avoid this low speed case, the minimum commandable speed is Vref, since there is no need to fly slower than Vref except for steep climbs. The engine is part of the protection system and the engine will always provide enough thrust to maintain Vref in level flight or a descent (except for some airplanes at high altitude – in which case the minimum commandable airspeed and AOA can be set to correspond to best climb speed). The pilot may command a climb angle that causes the airplane to decelerate below Vref. However, flying below Vref will always result in full power and will never result in an AOA greater than the programmed limit.

The AOA limit is set to the AOA that produces the best climb angle, or the AOA that is equivalent to stall warning AOA for conventional aircraft (stall speed plus a minimum of 5 kt), whichever is greater. Since stall warning is set such that it does not interfere with normal operations and normal operations includes climbing at the published best angle of climb speed, the best angle of climb speed cannot be less than stall warning speed. The maximum commandable climb angle should be set to be greater than the steady state maximum climb angle. Thus, to achieve the maximum climb angle the pilot simply pulls the stick back to the stop and holds it there (or locks it at the stop). The aircraft will “zoom climb” at the commanded angle while losing airspeed. When it reaches the AOA that corresponds to best angle of climb speed it reduces the pitch attitude to maintain that AOA.

The AOA limit can also come into play as the aircraft is banked and/or a change in flight path angle is commanded while above Vref. When this occurs, the aircraft flight controls honor the AOA limit to prevent a stall even though the speed is above Vref.

Terrain protection

In addition to the aircraft state limits, a minimum height above terrain was also enforced to prevent controlled flight into terrain. Of course, this minimum needs to be relaxed near airports to allow the airplane to land. This reduction in minimum height works similarly to the way that TAWS (Terrain Alert and Warning Systems) in current airplanes works. The software for this project was developed and tested with a simplified Auto GCAS (Automatic Ground Collision Avoidance System) protection system that simulates the terrain over Florida (constant altitude). The system needs to be expanded to include functionality similar to that developed by the Air

Force for F-16s in the 1990s [3], but the rudimentary system that was incorporated in this project shows such a system is compatible with the control system developed.

Protection integration

The protections (AOA, G, Pitch, Bank, High Speed, and Terrain) can conflict with each other. When this occurs, the aircraft executes logic that prioritizes them. For instance, if the airplane stalls, then it may not be able to control bank. In the simplest implementation, when the airplane is in a steep bank and the AOA limit is exceeded, the airplane will reduce up elevator to prevent a stall, but altitude will be lost. A more sophisticated implementation will recognize that the pilot is trying to maintain altitude and prioritize vertical flight path and AOA above the bank angle, thus reducing the bank angle to allow the system to reduce AOA and hold altitude. This will likely result in a safe but unpleasant ride as the bank angle rocks back and forth. An even better implementation uses the current aircraft speed and predicts the AOA to satisfy the bank combined with the commanded flight path change and then limits the bank command based on these predictions. This philosophy, when implemented seamlessly across all the protections, results in very smooth and natural transition between limits. This last example illustrates how the Navion implements these protections at the limits.

The certification implications of this set of protections for non-aerobatic airplanes is negligible except for the minimum allowable speed. The minimum allowable speed concept prevents the determination of the power off stall speed without special modifications to the airplane. Since many regulations reference stall speed, these need special consideration. A way to do this could be to choose a Vref then calculate the equivalent stall speed (divide Vref by 1.3) and show that the airplane can maintain level flight at this speed. Safe flight at the maximum AOA with climb power also would need to be checked.

3 EZ-Fly Prime Display system

The current conventional flight instrumentation was developed for the purpose of allowing a human pilot to control an aircraft directly through positioning the throttle, elevator, aileron and rudder of an airplane. It primarily displays aircraft pitch and roll attitude, altitude, airspeed, magnetic heading, and altitude rate since these are the aircraft states that the pilot most directly controls.

Since the control system closes the loop on attitude, direction, altitude, and airspeed, there is no need to display these in a manner appropriate for the pilot to use them in closing the control loop. With this in mind, a list of the pieces of information that a pilot needs along with the preferred display format for ease of use was developed.

For instance, since the control system closes the loop on attitude there is no need for an attitude indicator – synthetic vision may provide an indication of attitude, but if the terrain is sloped (as in mountainous terrain) this indication of attitude may be misleading. Since this does not present a problem, there is no horizon line to indicate attitude.

Another example is the display of airspeed. Since the control system closes the loop on airspeed, the pilot does not need trend information. Also, the only reason identified for the pilot to know airspeed is to be able to respond to an ATC request to report the current speed. In this case, the best way to display the information is digitally to the nearest 5 kt. Thus, the pilot can simply read the digits and then speak the digits – with no interpretation of graphics.

It was felt that the general public expects a moving map display for navigation (like an automotive GPS system) and a synthetic vision system as a forward-looking display background (if for nothing else) to reassure them that the aircraft is going where it is intended to go. These backgrounds were then used for a tactical (forward-looking) display and a strategic (moving map) display. It was determined that all other symbology must buy its way onto the display(s).

Since the pilot controls flight path directly, a flight path marker is included on the forward display. This display is track centric. This means that the flight path marker is always centered, and the synthetic terrain moves relative to it.

It was assumed that the aircraft would fly in today's ATC system under Instrument Flight Rules (IFR). In this environment, ATC asks for current altitude and airspeed, and assigns altitudes and airspeeds. Therefore, a digital display of current altitude and airspeed is provided along with a window to command altitude and airspeed changes. Note that there is no trend information for airspeed or altitude. This is not needed since the pilot is not part of the feedback control loop for airspeed or altitude.

ATC often assigns a heading. Therefore, a heading ring was included on the map display. The map display is appropriate since heading is more closely related to navigation and the map display is primarily a navigation display. Development of the map display was outside the scope of this project; therefore, the heading ring was put on the forward display for development purposes only (see Figure 2).

Figure 2. Forward display while holding a course

4 EZ-Fly Prime navigation system

The primary purpose of this aircraft is to travel to a destination using a flight plan – not to maneuver. Therefore, navigation is important. Nearly all current production aircraft have a very capable navigator connected to a moving map display. In addition, for older aircraft without modern avionics, many pilots carry portable navigators with moving maps. These moving maps, when they include a profile view, were close enough to what is required for intuitive depiction of a flight plan and the aircraft's position and orientation relative to it. The exception for the heading ring was discussed above.

However, it was determined that the depiction of the waypoints and flight plan also be shown on the forward display. A series of boxes, pavers, and other symbology that has been previously used to indicate a path on synthetic vision displays was considered but rejected due to its cluttering effect – and also the fact that the pilot of this aircraft does not need continuous guidance to maintain the flight plan track (see automation and integration in section 5, below). A magenta hoop was created at the next waypoint and the second waypoint on the forward display (see Figure 3). If the aircraft is tracking towards the next waypoint, the flight path marker will be centered in that hoop. When a waypoint has an altitude restriction, that waypoint is depicted at the appropriate altitude as well. If there is no altitude restriction, the waypoint altitude is at the current aircraft altitude. Waypoint information is also displayed around the hoop. This information includes the name of the waypoint, distance and time to the waypoint, and altitude restriction(s) of the waypoint if appropriate. The second waypoint is depicted in a darker color, is smaller, and has a scripted *i* at its center to indicate there is information there. If the user touches this waypoint, the above information appears in a text block (picture not shown).

Figure 3. Forward display capturing a flight plan

5 EZ-Fly Prime automation and integration

Since mode confusion is an often-cited problem with current Flight Management and autopilot Systems coupled to today's autopilots, a very simple interface was developed. This interface allows the functionality of a full Climb, Cruise, Descent, FAR 25-type flight management system (FMS) coupled to an autopilot and auto throttle system.

The current automation paradigm in certified aircraft is that the flight controls were developed first and their characteristics cannot be modified significantly. Next, the flight instrumentation was developed to match the flight controls and the basic information (attitude, airspeed, airspeed rate, altitude, altitude rate, heading and heading rate) must be presented. Aircraft location aids—such as non-directional beacons (NDBs), VHF omni-directional range (VOR) needles, etc.—were also added, and then later navigation aids like GPS track on a moving map. Autopilots were developed to hold certain aircraft states and to follow navigation tracks. However, these autopilots had to be specifically engaged and their mode of operation manually selected. Some autopilots would automatically transition from one mode to another if programmed to do so and some used different combinations of button presses to do the same things. Often different manufacturers labeled the same functionality differently. This resulted in automation mode confusion being blamed for many accidents and incidents. Part of this is because as automation developed, previous systems could not be changed to match the level of automation. For instance, as autopilots developed, the operation of the basic airplane with the autopilot turned off did not change significantly.

It was decided that the control, display and navigation systems needed to be developed as a single system instead of separate systems as has been done historically. The result of this decision was that developments in the navigation system could (and did) drive changes to the display and flight control systems. A change in any of these three systems could drive a change in any of the other two. This created a truly integrated control/display/navigation system or EZ-Fly Prime. This allowed the system to be designed such that it went seamlessly from one mode to another, using natural pilot commands. For example, selecting a heading automatically puts the system in heading hold mode and causes the airplane to track that heading; moving the stick laterally cancels heading mode and allows the pilot to command the flight path; putting the flight path marker on a part of the flight plan and centering the stick causes the system to fly to that part of the flight plan and then follow the flight plan. There is no such thing as turning the automation off or selecting the wrong mode of operation.

How a change in one system caused changes in other systems is illustrated by the design of the automatic coupling to a flight plan. Traditionally, the pilot selects a waypoint in the flight plan and selects direct to that waypoint, then selects NAV on the flight director mode control panel, and then engages the autopilot. In EZ-Fly Prime, the control system automatically couples to the flight plan when the flight path marker is put onto a waypoint and the stick is centered. This required changes in the display system to detect this condition and then in the control system to couple to the flight plan and then a further change in the display to indicate to the pilot that the coupling has occurred.

The result of this integration is that if the pilot is going towards a waypoint with the stick centered and is not on an assigned heading, the airplane is always coupled to the flight plan. If the pilot wishes to maneuver outside of the flight plan, simply moving the stick to command a turn out of the flight plan decouples the aircraft from the flight plan. There is no autopilot to engage or disengage. The airplane always captures selected altitudes, but these captures can be easily over-ridden by simply moving the stick longitudinally to modify the programmed vertical path.

This system was also designed to provide a natural step to fully autonomous flight by coupling to the flight plan before takeoff and allowing the aircraft to follow the flight plan including altitude and speed changes to a fully autonomous landing.

6 EZ-Fly Prime operation

The operating characteristics of an EZ-Fly Prime system are illustrated in the following video.

http://www.tc.faa.gov/its/worldpac/images/SVOVideo/SVOVideo.mov

7 Certification implications

The installation of the EZ-Fly Prime control, display, and navigation system and flight testing of the integrated system clearly showed that the current advisory material and even the new FAR 23 amendment 64 rules needed revision. Revisions are needed to both allow and properly regulate such a system.

For instance, current regulatory guidance requires the following to be displayed:

1. Attitude
2. Airspeed
3. Airspeed trend
4. Altitude
5. Altitude trend
6. Rate of climb
7. Turn and bank (or separate attitude indicator)
8. Magnetic heading
9. Lateral and vertical position of the aircraft relative to a navigation signal or reference

It also specifies the positions of these indications. These indications are presented as dials, tapes or needles. Unfortunately, in the EZ-Fly Prime implementation, these tapes or dials take up space without adding value.

With the EZ-Fly Prime control system, the pilot directly commands the flight path, therefore the flight path marker is important – especially relative to waypoints since lining up the flight path marker on a waypoint causes the control system to couple to the flight plan. Current certification guidance does not allow use of synthetic vision or a flight path marker to be used as flight guidance; it can only be used for situational awareness. The flight guidance must come from needles or pointers that show the position of the aircraft relative to a navigation signal or navigation reference. Thus, different certification guidance needs to be developed for the EZ-Fly Prime displays.

Although EZ-Fly Prime can be flown using conventional displays, they emphasize unneeded information and increase the pilot workload as compared to displays designed for the EZ-Fly Prime control system.

Another example of where the current certification requirements do not make sense for EZ-Fly Prime are the stall speed related rules. The EZ-Fly Prime system does not allow the airplane to fly below Vref (nominally 1.3 times stall speed) except when at climb power. At climb power or above, the airplane can fly as slow as Vx but not slower. Regulations more appropriate for EZ-Fly Prime would provide a maneuver margin and turbulence response when at these slow speeds instead of specifying stall characteristics.

Since there is no stall speed for an EZ-Fly Prime airplane, the regulations that reference stall speed are also not appropriate as written.

In the current regulations and guidance material, maximum speed limits (Vne, Vmo, Mmo) are set with the assumption that the airplane can exceed these limits due to pilot error or an upset. In addition, when above these limits, the pilot must take action to recover the aircraft while above these limits – therefore, handling characteristics requirements are imposed above these limits up to specified speeds higher than these limits. The EZ-Fly Prime airplane cannot be flown above these limits and if it is upset near the limits, it automatically recovers to within the limits without pilot input. Therefore, only recovery capability is required above these limits – handling characteristics requirements outside of these limits are irrelevant. Since for many airplanes, Vmo/Mmo are determined as the maximum speed at which these handling characteristics requirements can be met, the EZ-Fly Prime system can increase the maximum speed (Vmo/Mmo) of the airplane.

As the control system was changed from the AGATE Bonanza system to the Navion system, a lesson learned was how important it is to make the controls operate smoothly and seamlessly at the limits for inexperienced pilots. The Bonanza AOA protection worked well but was more like a conventional pusher in that it took over control and then gave it back to the pilot. For the more adventuresome non-pilots, this was not a problem – they understood that they could not hurt the airplane and this characteristic was part of the protection system that ensured that. The Navion system is seamless with regard to control limits and provides a smooth transition to and from the limits. In fact, the pilot usually does not even know when a limit is reached, the airplane just flies at maximum performance consistent with safety. For the less adventurous non-pilots, this was important in that they felt confident in their ability to control what the airplane was doing – and fly the airplane at its performance limits confidently. Because of this, it is recommended that certification requirements for reduced training in easy-to-fly aircraft mandate smooth operation throughout the envelope, including (and especially) at the performance limits.

In addition, because there is no manual engagement of the automation or pilot selection of automation modes, the current certification guidance regarding automatic flight modes and annunciations does not apply.

In addition to the regulatory guidance, the current rules (14 CFR 23 amendment 64) do not apply to EZ-Fly Prime in many cases. Table 1, below, identifies these regulations and makes suggested changes for EZ-Fly Prime and other EZ-Fly Prime-like concepts.

Table 1. 14 CFR 23 rules that need to be revised for EZ-Fly Prime

FAR 23 Amendment 64 rule	**Change needed for EZ-Fly Prime**
23.2005 Certification of normal category airplanes	(d)(1): Stalls does not apply to EZ-Fly Prime aircraft since the protections provided do not allow stalls to occur. Recommend deleting this.
	(d)(2): Lazy eights and chandelles may not make sense for the EZ-Fly Prime system. The purpose of these maneuvers is for the pilot to demonstrate mastery of the aircraft as it changes airspeed and attitude. With the EZ-Fly Prime system, the pilot simply directs the flight path and speed. The control system does what is required to satisfy the flight path and speed command. There is no mastery of the aircraft required with the EZ-Fly Prime system. Recommend deleting this for the EZ-Fly Prime system.
23.2110 Stall speed	Does not apply to EZ-Fly Prime. The minimum speed that EZ-Fly Prime can fly at other than full power is Vref. Vref needs to be determined such that there is adequate maneuver margin and gust protection. With full power, the airplane can fly as slow as Vx. There must be adequate maneuver margin and gust protection at Vx. Vx must not be greater than Vref. (Vx may not be the aerodynamic Vx, it may be the slowest speed that meets the maneuver margin and gust protection speed.) Recommend replacing this with a maneuver margin for Vref and Vx.
23.2115 Takeoff performance	Applies to EZ-Fly Prime as written except that (a)(1) “stall speed safety margins” should be replaced with “minimum flight speed safety margins.”
23.2120 Climb requirements	The balked landing climb requirement of (c) may not apply to EZ-Fly Prime aircraft. These aircraft will likely have other SVO features such as automatic configuration control, so that when a go around is initiated the aircraft is automatically configured. In this case, it is impractical to require a climb gradient in the landing configuration. Recommend adding a provision that aircraft that automatically configure to the climb configuration on go around need not comply.
23.2130 Landing	For EZ-Fly Prime, b(1) and (2) should be replaced with “minimum touchdown speed.”
23.2135 Controllability	(a)(3): FBW control systems are non-reversible. If the intent is to mean failures that can be corrected then it applies. Recommend changing the wording for (a)(3) to “With likely flight control or propulsion system failures that can be corrected; and”

FAR 23 Amendment 64 rule	**Change needed for EZ-Fly Prime**
23.2140 Trim	(a)(1) appears to be a concession for small airplanes that typically don't have trim in all axes. With FBW, there is no need for this concession. Recommend making (a)(2) apply for all FBW aircraft.
	(b): For EZ-Fly Prime, (b) does not apply since the system is always in trim for flight path stability, there is a means to eliminate the force for long climbs and descents, and the AT system provided the speed stability.
23.2145 Stability	(a)(1): See discussion above (trim) for longitudinal stability.
	Lateral stability as typically understood (the ability to raise a wing with rudder) does not apply EZ-Fly Prime. EZ-Fly Prime provides lateral stability by introducing bank stability. Bank stability is what we really want but usually don't get with mechanical control airplanes, so we provide dihedral effect and call it lateral stability. EZ-Fly Prime needs (a)(2) to have "lateral" removed and replaced with "bank."
	(a)(2): EZ-Fly Prime needs (a)(2) to also include dynamic bank stability.
	(a)(3) Applies to EZ-Fly Prime, however the type of stability may be different. The EZ-Fly Prime system can "lock" a flight path such that the concept of force does not make sense.
	Suggest replacing this rule with something like the following. "All aircraft must be statically stable related to their commanded state (roll rate, bank angle, lateral velocity relative to heading, etc.), and must be dynamically stable about that state with heavy damping (heavy damping to be defined, but somewhere between deadbeat and less than 1/10th amplitude in 1 ½ cycles)."
23.2150 Stall characteristics, stall warning, and spins	(a)(b): Stall protection is an integral part of EZ-Fly. Therefore, this rule does not apply as written. However, there needs to be some criteria for minimum flight speed (maximum AOA) that will allow for gusts, rapid command changes and minimum maneuver capability (such as turn rate). This minimum speed may be near the current stall warning AOA.
	(c): This rule should be applied to but replace "from thrust asymmetry after critical loss of thrust" with "from any failure."
	(d)(e): EZ-Fly Prime does do not allow aerobatics. Therefore, these rules do not apply.

FAR 23 Amendment 64 rule	Change needed for EZ-Fly Prime
23.2160 Vibration, buffeting, and high-speed characteristics	(a)(b): Applies to EZ-Fly Prime written except that stall warning buffet should not be allowed since the minimum speed will be about where current stall warning is or higher.
	(d)(2): This rule applies to EZ-Fly Prime except that "trim upset" should be replaced with "flight control system failure" and "longitudinal trim system" replaced with "longitudinal control system."
23.2165 Performance and flight characteristics requirements for flight in known icing conditions	(a)(2): Stall warning has no real meaning for EZ-Fly Prime with the described protections. Suggest deleting this rule.
23.2200 Structural design envelope	(a)(1): Replace "stalling speed" with "minimum speed" for EZ-Fly Prime aircraft.
23.2215 Flight load conditions	Applies to EZ-Fly Prime, as written but add "failure of control systems" - possibly as paragraph (d).
23.2245 Aeroelasticity	Applies to EZ-Fly Prime, as written but make it clear that the control reversal mentioned here is relative to the inceptor, not a control surface.
23.2250 Design and construction principles	(d): Reword this rule to allow the conditions listed as long as the pilot input to vehicle output mapping is not adversely affected. (Excessive friction is allowable for FBW as long as the actuator(s) can overpower it.)
23.2300 Flight control systems	(b): This does not apply to the EZ-Fly Prime system since there is no trim in the sense that it is described by this rule.
23.2405 Automatic power or thrust control systems	(d)(2): EZ-Fly Prime, by design, has a full time automatic power system and it is assumed that the pilot trained to operate an EZ-Fly Prime system would not know how to control the aircraft by manual control of the power system. These aircraft may need to rely on the "extremely remote failure" clause. However, this would also preclude novel solutions to failure cases that are safe and for which failure of the automatic power control system is not extremely remote. 23.2405(d)(2) needs attention. Maybe the best solution for EZ-Fly Prime is to require the automatic power system to have the same reliability as the rest of the flight control system.

FAR 23 Amendment 64 rule	Change needed for EZ-Fly Prime
23.2540 Flight in icing conditions	(b): For EZ-Fly Prime, this should be changed to prevent the airplane from flying at a speed less than the minimum speed for icing conditions – the minimum icing speed should be determined such that it provides a similar safety margin as the non-icing minimum speed. Also, the statement about the autopilot should be removed for both EZ-Fly Prime. The control system should prevent flying too slow all the time.
23.2600 Flight crew interface	(b): Applies to EZ-Fly Prime, except that there may be no powerplant controls or displays. If this is the case, it should be made clear that this is acceptable.

8 Development decisions and issues

8.1 Active stick

It was desired that the final product utilize a passive stick (no system programmable actuators). However, an early decision was made to use an active (software programmable actuators) joystick for development. An active joystick allowed changes to spring rate, dead band, friction characteristics etc. to be made in software without building new hardware. This turned out to be a very good decision. It allowed rapid iterations of different logic schemes and actuation models to develop the longitudinal stick lock feature. The result is a stick lock feature with a friction plate that clamps down on a spring-loaded stick. This holds the stick in place with just enough force to overcome the spring force, and then releases the plate when the lock is released.

8.2 Vertical flight path stick lock design

One of the issues identified on the AGATE Bonanza was that for long climbs or descents, the pilot had to hold a force on the stick to maintain the climb or descent. This was unacceptable. Therefore, one of the goals of this project was to develop an acceptable means of relieving the pilot force during long climbs and descents. However, one of the strong safety features of EZ-Fly was that if the pilot became confused, they could simply let go of the stick and the aircraft would fly straight and level. The need to provide a zero-force way to climb or descend, and the desire to retain the “automatic level flight” feature appeared to be conflicting requirements. In an attempt to reconcile these requirements, several designs were considered. Three of the leading options are described below.

8.2.1 Move the center position using a trim switch

Longitudinal stick position commands a flight path angle. The longitudinal stick behaves like a centering spring. However, during a long climb or descent, the pilot can use the top hat switch to trim out the forces. The spring center moves in the direction the switch is pressed. Small corrections can still be made because the stick is not locked in position. To return the aircraft to level flight, the pilot presses a different switch and the spring re-centers at zero flight path angle.

8.2.2 Set the current position as the centered position

Longitudinal stick position commands a flight path angle. The longitudinal stick behaves like a centering spring. However, during a long climb or descent, the pilot can press and release a push button that re-centers the spring to the current longitudinal stick position. This allows the pilot to set the center point to a non-zero flight path angle. Small corrections can be made because the stick is not locked in position. To return the aircraft to level flight, the pilot presses the same push button and the spring re-centers at zero flight path angle.

8.2.3 Lock the stick

Longitudinal stick position commands a flight path angle. The longitudinal stick behaves like a centering spring. However, during a long climb or descent, the pilot can press a push button that locks the stick in its current longitudinal position. To return the aircraft to level flight, the pilot has two options: 1) push the same button, or 2) apply an overpowering force of 10 lb. to the longitudinal stick.

8.2.4 Design selection

The above design concepts along with several others and variations of the above designs were evaluated by multiple pilots using the man in the loop ground simulation. Evaluation pilots had various levels of experience ranging from people familiar with flying but who did not have a pilot license to people with thousands of hours of flight time in many different types of aircraft.

Since the EZ-Fly Prime system was designed for people who currently do not have flying experience, the opinions of the pilots with little or no pilot experience were given more weight than those of pilots with extensive flying experience. The group chose the “Lock the Stick” option described in Section 8.2.3.

To relieve the force in a long climb or descent the pilot could lock the stick at the position to command a climb or descent. To make an adjustment, they could press the button, move the stick slightly and release the button, which would then lock it in the new position. In addition, if the pilot got disoriented, they could simply bump the stick and the airplane would go to straight and level flight. After flying this in the airplane, pilots of all experience levels quickly learned to operate this feature correctly without issues.

Note that the final design can readjust the stick position by pressing and holding the button. The original design did not have this feature – but it was found to be important. It took several attempts to find the right time for the button to be held down to distinguish between “release to zero” and “reset to the current position”. It was found that 0.25 seconds was about right as the switch point (holding the button down for less than 0.25 seconds was a “release to center” command and holding it for more than 0.25 seconds was the “reposition the hold location” command). For some, it seemed easier to just physically move the stick when a “release to center” command was desired instead of doing a short press.

8.3 Control law development and tuning

The development and tuning of the EZ-Fly Prime control laws occurred using three distinct phases. These were 1) desktop algorithm development and tuning, 2) man-in-the-loop simulator development and tuning, and 3) tuning in flight. During the program, all three phases occurred simultaneously as different functions and features matured at different rates. This required close coordination between the phases. The desktop development and tuning were done primarily at an office near Kansas City, Kansas while the man-in-the-loop simulations and flight testing were done near Daytona Beach, Florida.

8.3.1 Initial desktop development and tuning

The algorithm development was done on a desktop computer using a high-fidelity Simulink model of the Ryan Navion. The control algorithms were also developed using Simulink. The initial tuning was accomplished by running the Simulink model of the Navion and control algorithm using predefined stick inputs, and then examining the resulting aircraft motion using Simulink “strip charts.” Various sets of stick inputs were developed to exercise the various aircraft axes and control law features. The control laws were developed such that they could be tuned extensively using gains read from a gain file instead of requiring a change of the actual algorithm. This was done to provide maximum tuning flexibility during the man-in-the-loop simulation and flight test phases without requiring the control system to be sent back to the desktop phase. When the control laws were tuned to obtain satisfactory performance, as observed by the strip chart data, the Simulink model and associated gain set was sent to the man-in-the-loop simulator for testing.

8.3.2 Man-in-the-loop simulator tuning

The Simulink model from the desktop development was loaded into a real-time simulation that included multiple large screens to display an outside view along with a Heads-Up Display (HUD) to indicate airspeed, attitude, etc., as it would be displayed using a glass cockpit type of display. This simulation was then flown by multiple pilots. Video of the outside view and HUD was sent back to the desktop simulation for additional algorithm development and gain tuning. When the man-in-the-loop simulation was acceptable, the simulation was moved to the aircraft, which had a simulation of itself such that its simulation would respond to real control system inputs, but the aircraft would remain in the hangar while doing this. This allowed the control system to be operated with real hardware in the loop using real transport delays and other artifacts of real hardware. Again, video and pilot comments were reported, and the system sent back to the desktop stage as needed. However, at this stage many of the changes required could be accomplished through gain changes instead of algorithm changes. The early decision to create the algorithms so that they could be tuned using gains read from a file paid big dividends during this phase and the flight-test phase.

8.3.3 In-flight tuning

When man-in-the-loop simulations and aircraft-based ground simulations performed satisfactorily, control laws were turned on in flight one axis at a time. Testing began using simple maneuvers and progressed to realistic flight demonstrations through a classical buildup approach. The aircraft software was set up so that selected gains could be changed in flight. This ability allowed rapid tuning compared to flying with a fixed set of gains, recording the data, landing, evaluating the data and then determining a new set of gains for the next flight. To do so safely, the airplane features a hardware-based monitoring system that disconnects the electronic controls if the airplane exceeds any predefined limits. Also, the safety pilot had multiple switches that would disable the electronic control system immediately. Since the airplane flight control surfaces were mechanically connected to the safety pilot’s controls (the safety pilot’s controls were the standard Navion mechanical controls), the safety pilot could also disconnect the electronic controls when they started to move in a manner different (or faster) than expected. When the electronic controls were disconnected, the safety pilot could fly the airplane as a standard Navion.

To date, the contract has flown a total of 132.4 flight hours. A breakdown of those hours includes; 84.5 flight hours for EZ-Fly Prime testing and in-flight tuning, 28.3 hours for display testing and tuning, and 19.6 flight hours for FAA evaluations.

8.4 Determining the appropriate performance level

One of the interesting aspects of this project was determining the appropriate level of performance. The airplane is used as a tool to determine appropriate means of compliance and for technology demonstrations. It is not intended to be a product. As such, it does not need to have the performance level for holding altitude, airspeed, flight plan track, etc. as would be expected for a real product. Determining the appropriate level of performance was extremely challenging.

For most development projects, as the project matures, it takes more effort and resources to make smaller changes. This is illustrated by the graph below (see Figure 4).

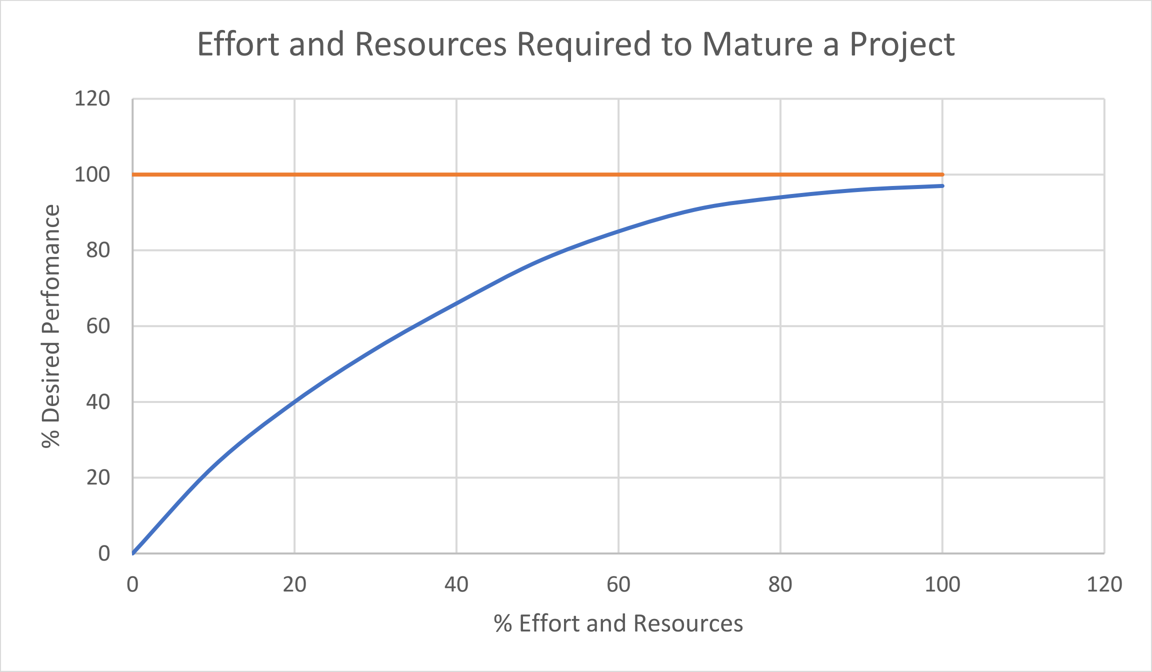


Figure 4. Typical effort required to improve a project

Spending the time and resources to improve the performance of the system takes considerable time, especially as the system matures. Projects developed to be a product can often be evaluated against perceived customer performance expectations. This project was not intended to be a product, but was intended to develop means of compliance for highly augmented Fly-by-Wire control systems such as EZ-Fly Prime. As such, the project did not contain resource allocations that would be associated with developing it to be a product. There were, however, expectations that the system would be demonstrated to select test pilots and some non-pilots in a "guest pilot workshop" environment, with the expectation that the guest pilots would understand that it is a concept prototype.

8.5 Research interconnections

As the project matures in a research and development environment, it uncovers issues that need further development to resolve. Also, the end goals often change as the project matures. This occurred several times in this project.

As the control system was developed, it became clear that using a conventional flight display did not fit well with the control system (this was also a conclusion from the AGATE work). Then, as the display was developed to fit the control system, it also became clear that navigational functions (i.e. a flight plan) needed to be included in the automation. As discussed above, this led to the conclusion that integrating the control, display, and navigation system was required. This then led to re-designing parts of the control and then display systems to accommodate the automated functionality of the navigation system.

Often a project suffers from scope creep, in which the scope of the project increases over the original plan. The addition of the displays, then navigation, and then integration could be considered scope creep, considering the original plan was simply to duplicate the AGATE system and incorporate lessons learned during that activity. However, in this case, since the objective is to develop a means of compliance for highly automated aircraft, the addition of these originally unplanned tasks become required to meet the objective.

These issues of redefining the objectives and changing the target audience of the guest pilot workshop to primarily non-pilots made it difficult to manage the budget as the project developed.

8.6 Appropriate evaluation pilots

The EZ-Fly Prime system is designed and intended to be a system that is easy for non-pilots to learn to fly. The EZ-Fly Prime system was extended to include protections and a high level of automation with intuitive operation of the automation while still allowing the pilot to command the flight path manually.

The principle developer of the original EZ-Fly system at NASA had no flying experience and credited that lack of flying experience with his ability to develop the EZ-Fly system. By contrast, the principle developers of the EZ-Fly Prime system are very experienced pilots and flight instructors, and some are very experienced pilot human factors evaluators using traditional pilot human factors criteria. There was a constant awareness that it is difficult to discount that experience and continually reinforce the concept that the system was not being designed for experienced pilots.

Previous experience with EZ-Fly in the AGATE Bonanza, which did evaluations with both experienced pilots and non-pilots, found that very experienced pilots generally did not find value in the EZ-Fly system; however, non-pilots found it extremely valuable. In fact, the AGATE Bonanza flights with very experienced pilots found that for high workload tasks like flying an approach, the workload for experienced pilots was higher with EZ-Fly than with conventional controls, but the workload for non-pilots flying the same task was lower than the task for experienced pilots with either system. The conclusion from this was that flying an approach with conventional controls is a high workload task, and experienced pilots flying this task using EZ-Fly had to deal with negative transfer. For example, their normal reactions to gusts was not correct for EZ-Fly, and this created an extra workload. The non-pilots did not have a set of previously developed normal reactions to gusts and did not experience the negative transfer.

Another example is a response to a gust that causes a small bank upset. The EZ-Fly system is designed to fly the airplane along the commanded path, when a gust causes a small roll upset, the EZ-Fly system immediately counters the upset without any input from the pilot. The non-pilots just ignored the upsets because they didn’t have to do anything about them – much like running over a bump on the road in a car. In a conventional control system, the pilot controls the attitude of the aircraft by commanding a roll rate (there is no bank angle stability – that is provided by the pilot). When the airplane is upset, the pilot must take action to keep it level. The experienced pilot has learned through thousands of hours of piloting experience that to fly the best approach, when a roll acceleration is felt, that they must counter that roll acceleration before it turns into a roll rate and then a bank angle. This response to a gust when flying the EZ-Fly system commands the airplane to turn. Thus, the experienced pilots would generally be very active on the lateral control during an approach – the first response to a gust was unnecessary, but the next pilot input was necessary to correct the turn that the pilot had inadvertently commanded. The non-pilots just left the stick centered except for minor occasional inputs to adjust the commanded path.

Taking this lesson into account and to ensure that the system was being developed such that it is optimized for non-pilots, people who had little or no aviation experience were often used as evaluation pilots. It was found that people have very different reactions to being in control of an airplane for the first time – even if control is easy and you can’t get yourself or the airplane into trouble. Some took the controls readily and started controlling the airplane confidently almost immediately. Others were very timid with the controls despite being told repeatedly that they cannot hurt the airplane or the people in it. In all cases, the subject was able to control the aircraft and execute aggressive maneuvers including 45-degree banked turns confidently in less than an hour.

For some of the more confident subjects, after the session of flying EZ-Fly Prime, the airplane's control system was switched to mimic the flight characteristics of a standard Navion. It was interesting to observe how uncomfortable they were with the basic Navion handling characteristics (typical of a FAR 23 general aviation airplane) and how they strongly preferred the EZ-Fly Prime system.

Experienced pilots were not used as evaluation pilots, other than the developers themselves to develop and tune the system.

8.7 Airspeed sensor issue

The system in the Navion was intended for development of the algorithms and not intended to have the reliability required of a certified system, nor was it intended to explore failure modes or reliability issues. Therefore, it was designed as a single thread system with no redundancy for the FBW functionality. System safety came from the fact that the FBW system could be disengaged easily by the evaluation pilot, the safety pilot, or automatically if certain parameters were exceeded. When the FBW system is disengaged, the safety pilot has full control of the aircraft through the normal Navion reversible mechanical control system.

On one of the flights an air data anomaly occurred. The anomaly caused the FBW system to sense airspeed 10 to 15 knots too high. Because the FBW control system used the erroneous airspeed, the system controlled the airspeed to a speed 10 to 15 knots below the commanded speed. However, the erroneous speed was also displayed such that the commanded speed and the displayed speed matched while the airplane was going slower than the displayed speed. This caused many seemingly unrelated behaviors. Because the air data issue provided erroneous information to both the display and the control system, the crew did not recognize the failure – even though two of the crew members on the flight were very familiar with the system and its operation. An overview of the event is provided below.

The minimum commandable airspeed is 80 knots, the AOA in level flight at this speed is about 8 degrees. The flight control AOA limit is set to about 11 degrees, which occurs at about 70 knots in level flight. Stall AOA is about 14 degrees, which is at about 63 knots. The airplane is in stall buffet but not stalled at 14 degrees.

During the flight, the crew heard the high AOA aural several times during maneuvering and the AutoGCAS recoveries.

During the evaluation, when minimum speed (80 kt) was commanded in level flight, the throttle system slowed the airplane toward an indicated airspeed of 80 kt, which was a calibrated airspeed of about 65 kt. Thus, the level flight AOA became higher than 11 degrees and AOA limiting started occurring. The result was that the flight path command was being over-ridden by the AOA protection and the airplane started descending. The airplane was descending at an indicated airspeed higher than the commanded airspeed and therefore the throttle was commanding low power. The airplane was in a slight descent at low power at the AOA limit, which corresponded to about 70 kt while indicating 85 kt with a level flight command of 80 kt and the high AOA aural was sounding. (Note that with a normally operating airplane, the airspeed can never get below the minimum commandable speed without full power.) The crew's observation was that with a level flight command at 80 kt, the altimeter was slowly moving (showing a descent) and the word HOLD was displayed beside the altimeter.

A similar situation occurred while testing the AutoGCAS function. The airplane was on the AOA limit as described above and slowly descended slightly below the AutoGCAS floor with the airplane in a turn and in stall buffet. The ground protection and the stall protection were in conflict with each other at this point with the bank protection also being involved. Note that these protections worked together to get the airplane to its lowest energy state, while avoiding a stall and still allowing limited bank for maneuverability.

The big picture of this research project is not to develop an EZ-Fly flight demonstrator – it is to gain knowledge for MOCs that will work in the real world when FAR 23 manufacturers come with FBW control systems – especially when these manufacturers don't have the engineering depth of established manufacturers that have brought FAR 25 and FAR 29 FBW aircraft to the market.

Reliability, architecture, run time assurance, and flight control laws are all tangled up together in real world aircraft. The flight with an erroneous airspeed sensing system provided much insight into how MOCs and task elements should be constructed.

On this flight, the aircraft experienced a failure that was subtle enough that the crew did not recognize it but prevented the system from operating as intended. There was no redundancy or monitoring of the failed system in this airplane. However, there were integrated protections in the flight control algorithms. The result was that the protections kept the airplane from stalling and correctly prioritized themselves. This is an example of how safety can be built into the flight control algorithms. Note that AutoGCAS was incorporated into the protections – not implemented as a run-time assurance function. If it had been implemented as a run-time assurance function, it would have over-ridden the protections and prevented the airplane from going below the floor – causing a stall and then going below the floor out of control.

The implication of this flight for task element development is significant. Note that if the airspeed had failed such that airspeed became unavailable, it would have had a much different effect on the flight. Data becoming unavailable is relatively easy to detect and relatively easy to design for. Erroneous data can be much more difficult to detect and design for. Note also that this type of failure could have been duplicated in a simulator. In fact, many failures like this can be simulated very quickly. This underscores the value of task element simulators with the ability to simulate failures of various types – often failures specific to the configuration and architecture of a vehicle.

This experience underscored the need in a certified system to understand the effects of failures and either design the system such that failures have little or no effect on system performance, or provide clear annunciations and directions to the pilot concerning required actions when failures occur. With an integrated system such as EZ-Fly Prime, it is unrealistic to expect a pilot to be able to understand and diagnose failures.

The history of accidents involving the effects of failures in highly integrated systems has indicated that relying on pilot action to ensure continued safe flight and landing after a failure may not be appropriate. Therefore, for certified systems it is important that the system be designed such that failures have little or no effect on the aircraft’s ability to continue safe flight and landing. History also indicates that pilots can get “consumed” by trying to diagnose a perceived or real failure and cause an accident by erroneous pilot action. This underscores the need in highly integrated systems for the system to diagnose and deal with its own failures, and not expect the pilot to take action to continue safe flight and landing.

8.8 Annunciation philosophy

Although the system as tested is a single thread system, it is expected that such a system in a certified aircraft will require a very high level of reliability. Also, due to interactions of the various parts that may not be obvious, it is also expected that pilots cannot be expected to diagnose problems and reconfigure the system in flight. For these reasons, a fail operational system architecture is required such that the system automatically reconfigures itself when failures occur, and that the system has enough redundancy that it can continue safe flight and landing after the failure without pilot action.

With current aircraft design, the pilot is expected to understand the systems and manage them. This includes reconfiguring system due to failures and possibly observing aircraft limitations changes due to failures. For this type of design, it is very important that the pilot understand the status of the various systems.

However, if the systems are designed to manage themselves and when a failure affects an aircraft limit, the control system honors that limit automatically, then the pilot does not need to know the status of the systems other than maintenance is required and it may be required before the next takeoff. Thus, systems status annunciations introduce unnecessary clutter and distraction. With this type of system, an annunciation that indicates how many flights are allowed before maintenance is required may be the only required annunciations.

9 Unfinished work and needed follow on work

9.1 Speed control knob

The system as developed used a lever marked in knots of indicated airspeed. This concept came from the AGATE Bonanza where it worked well. As the integrated control/display/navigation system was developed, it became clear that this lever concept needed to be changed. The navigation system can change the commanded airspeed. If the speed command lever was retained, it would have to be back driven - like most auto throttle systems back drive the throttle levers. However, the speed command lever has hard stops at its travel limits, which are used to command the maximum and minimum speed. When setting up for an approach this is very convenient because the pilot can simply move the lever to the aft stop and be assured that the airplane will slow to the minimum commandable speed (approach speed), or to the forward stop and be assured that the airplane will go no faster than the maximum commandable speed for that flight condition. The problem comes when the airplane's maximum or minimum commandable speed changes (such as when changing configuration, changing altitude or going into a different class of airspace). When the speed limits change, the physical stops must change too, or the stops cannot be used to denote the commandable limits.

A solution to this is to use an indexless knob that has no stops, much like the volume knob on a car radio. This is also the solution used by many Flight Management Systems that couple to an auto throttle system. Turning the knob to the right increases the commanded speed until the limit is reached. The knob can be turned more, but the commanded speed does not increase. The opposite occurs at the low speed end. In addition, when the navigator is controlling the speed from the flight plan, it can do so without turning the knob.

It is recommended that further work with the EZ-Fly Prime system use a knob without stops, as opposed to a speed command lever.

9.2 Navigation including visual flight rules (VFR) approaches

This project did not include any work on a navigation system (FMS or equivalent). For this work, a specific flight plan was created and incorporated into the display/control code. This flight plan included several waypoints with altitude and airspeed changes. For situational awareness, a moving map display from Foreflight™ was used, and the flight plan was entered into the Foreflight™ system. This mimicked the required communications between a moving map display and the forward display/control system – but only for this very specific flight plan.

Further work is needed to create a moving map and flight plan that is as simple to program as the EZ-Fly Prime system is to fly. It may be that a Foreflight™ type of interface is good enough, but this needs to be verified by creating a "live" flight plan that integrates with the EZ-Fly Prime system.

It also became obvious, in the course of developing and flying the EZ-Fly Prime system, that pilots with little experience had no concept of how to enter a traffic pattern and set up for a landing. This is consistent with accident data for general aviation pilots as well, since most loss of control accidents occur in the traffic pattern. The conclusion was that we needed to develop a system that would create VFR approach paths automatically. The display/control system would treat them like flight plans. The pilot would couple to a VFR approach automatically simply by putting the flight path marker on a waypoint and centering the stick. The control system would then couple to the flight path and control the lateral, vertical and speed of the aircraft to the runway.

There will be many certification implications to a system that automatically creates VFR approach paths. These implications include obstacle avoidance, non-standard approaches as requested by ATC ("extend downwind, I'll call your base", etc.), tracking performance requirements, etc.

9.3 Takeoff and landing

This project was only concerned with flight away from the ground. It did not consider takeoff or landing. An obvious next step is to include takeoff and landing. A major question concerning takeoff and landing is how much automation should be required and how much manual control should be allowed.

9.4 Vertical takeoff and landing (VTOL) operations

With the advent of the emerging Urban Air Mobility industry and their desire for reduced pilot training/proficiency costs and increased automation, a natural extension to EZ-Fly Prime is vertical takeoff and landing capability. Some questions, among many others, include the following:

- How do the control inceptors for EZ-Fly Prime map to vehicle motion during vertical operations?
- Do the current EZ-Fly Prime inceptor to vehicle motion mappings need to change to be consistent with VTOL operations?
- Does there need to be a separate set of inceptors for VTOL operations and fast forward flight?
- How much automation is appropriate?
- How much deviation from a defined path should the pilot be allowed during VTOL operations?
- What protections are appropriate for VTOL aircraft, as opposed to the traditional protections incorporated into EZ-Fly Prime?

10 Conclusions

The installation of the EZ-Fly Prime system on the Navion and then flying it was important in at least four ways.

1. It verified the recommended changes to EZ-Fly from the AGATE Bonanza program and, in so doing, significantly moved the system forward towards its goal of creating a flight control system that takes advantage of FBW technology to dramatically improve safety to General Aviation, while simultaneously lowering the training and proficiency barrier for pilots.
2. Flying the EZ-Fly Prime system while developing it was extremely valuable for the integration of the displays and navigation system with the control system.
3. Flying the system using non-pilots was very valuable in understanding the needs of people who can benefit from the reduced training and proficiency requirements, while making it impossible for them to lose control of the aircraft.
4. Flying the airplane while examining the current rules and guidance material was invaluable in identifying the rules that need to change and then providing recommended changes.

An initial conclusions presentation was presented at the General Aviation Manufacturers Association (GAMA) meeting in November 2018 and is included in Appendix B.

11 Recommendations

The current project only deals with climb, cruise, and enroute descents. The project created a design that works very well for non-pilots to maneuver the airplane, follow an assigned heading, capture and hold an assigned altitude, control speed and automatically couple to a flight plan with less than an hour of in-flight training and without any signification ground school (a safety brief was provided prior to each flight). This should be considered a strong success. However, the project did not cover all aspects of a flight.

It is recommended that the project continue to include the following phases of flight.

1. Takeoff
2. VFR approaches
3. Landing

In addition, flight planning including routing, weather, NOTAMs etc. needs to be examined so that an automated preflight system can be developed.

One of the most confusing aspects of learning to fly in instrument conditions is communicating with ATC. Since the EZ-Fly Prime system has developed a way for the pilot to intuitively couple to a flight plan, a way to simplify ATC communication may be to create a means by which ATC communicates through the flight plan directly – not via voice. This may be done using voice recognition and text to speech, or by other acceptable means.

Automatic ground collision avoidance (Auto GCAS) is an important aspect of the EZ-Fly Prime concept that was only touched on in this project. The control system was programmed to demonstrate the capability to react to terrain threats, but only a very rudimentary escape path was developed. This concept needs to be fleshed out much better.

While the flight-planning item can be done using ground simulations only, and the ATC part can be done largely by using ground simulations, actual flight tests with inexperienced subjects will be required to develop the appropriate MOCs for Takeoff, VFR approaches, landing, AutoGCAS and some of the ATC parts.

12 References

1. Stewart, E. “A Piloted Simulation Study of Advanced Controls and Displays for General Aviation Airplanes”, AIAA Paper 94-0276, January 1994.

2. Duerksen, N. “Advanced Flight Controls and Pilot Displays for General Aviation”, AIAA Paper 2003-2647, Dayton Ohio, July 2003.

3. Skoog, M. “Advanced Fighter Technology Integration/F-16 Automatic Ground Collision Avoidance System Evaluation”, AFFTC-TR-99-28, Air Force Flight Test Center, Edwards AFB, California, December 2000.

A Appendix A: History of EZ-Fly development

INITIAL DEVELOPMENT OF EZ-FLY (LATE 1980S)

Purpose

The EZ-Fly concept was developed in the late 1980s at NASA Langley [1]. The purpose of the EZ-Fly system was to develop and then demonstrate a Fly-by-Wire system that could dramatically reduce general aviation pilot training and proficiency requirements. The system was used to conduct a series of simulator tests and demonstrations, with primarily non-pilots, in order to show the potential of FBW and advanced displays for general aviation.

Control system

In this system, the longitudinal stick position commanded vertical rate, the lateral stick position commanded bank angle, the rudder pedal position commanded sideslip angle and throttle commanded speed. The longitudinal and lateral stick position had automatic trim such that when the stick was moved and held in a position for several seconds, it would remain in that position without a force being applied.

Display system

The EZ-Fly display system was primarily a Heads-Up Display (HUD) system that had many features designed specifically to match the control system. The "HUD" had symbology projected onto the forward screen of the simulator to resemble a heads-up display. The HUD had highway in the sky (HITS) symbology that incorporated a series of boxes and "highway" edge markers connecting the boxes. It also had a command arrow to indicate to the pilot the direction to fly when not near the center of the desired path.

Navigation

There was no navigation system in this implementation. The path, which included takeoff, straight climb, climbing 180-degree turn, level flight segment, descending 180-degree turn, straight descent, and landing (with flare guidance) was permanently defined by the HITS path in the HUD (see Figure 5).

At the time, it was thought to be important that the pilot always be in the loop to control the flight path (except during long cruise segments). The simulations included takeoffs and landings in turbulence and crosswinds.

Figure 5. Simulator with EZ-Fly controls and highway in the sky heads-up display

DEVELOPMENT OF EZ-FLY IN THE AGATE BONANZA (LATE 1990S)

Purpose

The EZ-Fly system developed by NASA Langley was installed with modifications in a Beech F33C Bonanza during the NASA/Industry Advanced General Aviation Transportation Experiments (AGATE) program during the late 1990s. The purpose was to test the concept in a real airplane in real flight conditions. This aircraft was flown on many long cross-country flights and demonstrated to many people – both pilots and non-pilots.

Control system

The EZ-Fly system as described above was installed in the AGATE Bonanza except for the following changes [2].

1) The trim system was eliminated. The Bonanza only had a spring centered stick – not a force feedback stick – and therefore could not implement the trim system. The lateral trim system in the EZ-Fly simulations did not provide value and in some cases was detrimental. The longitudinal trim system did provide value. It was found with non-pilots that, while maneuvering, the concept of simply letting go of the stick to go straight and level was very powerful in providing confidence and safety. The resulting need to hold the stick against a spring for long climbs and descents was recognized as a deficiency.
2) The longitudinal stick commanded flight path angle instead of vertical velocity. This was to facilitate descents and approaches where the airspeed is changing.
3) The lateral stick commanded bank angle with a changing scale that reduced the commanded bank angle as airspeed was reduced to avoid a stall at low airspeeds and high bank angles.
4) Stall, overspeed, over bank and over G protections were incorporated. These protections were invaluable for non-pilots to provide confidence and safety.
5) There was no sideslip capability; the rudder functioned automatically to provide yaw damping, turn coordination, and compensation for torque and P-factor.

Display system

The Bonanza did not have a HUD. There were two head down screens. The primary flight display (PFD) had synthetic vision with HITS like today’s PFD displays. The multi-function display (MFD) was a moving map like today’s MFD displays. Neither synthetic vision nor a moving map display were generally available in new aircraft at that time.

Navigation system

The system had the ability to display flight plans including instrument approach paths on the MFD. It could also display a set of boxes on the PFD to indicate the flight plan path (see Figure 6).

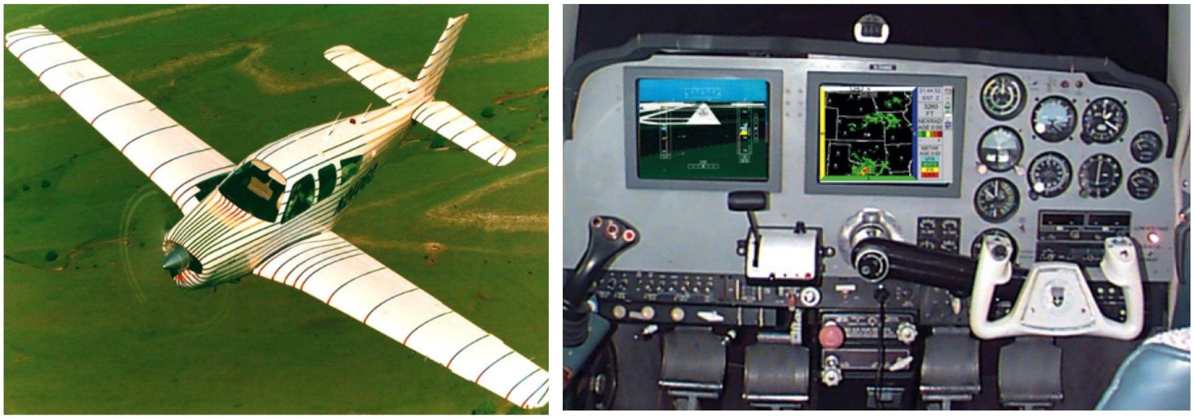
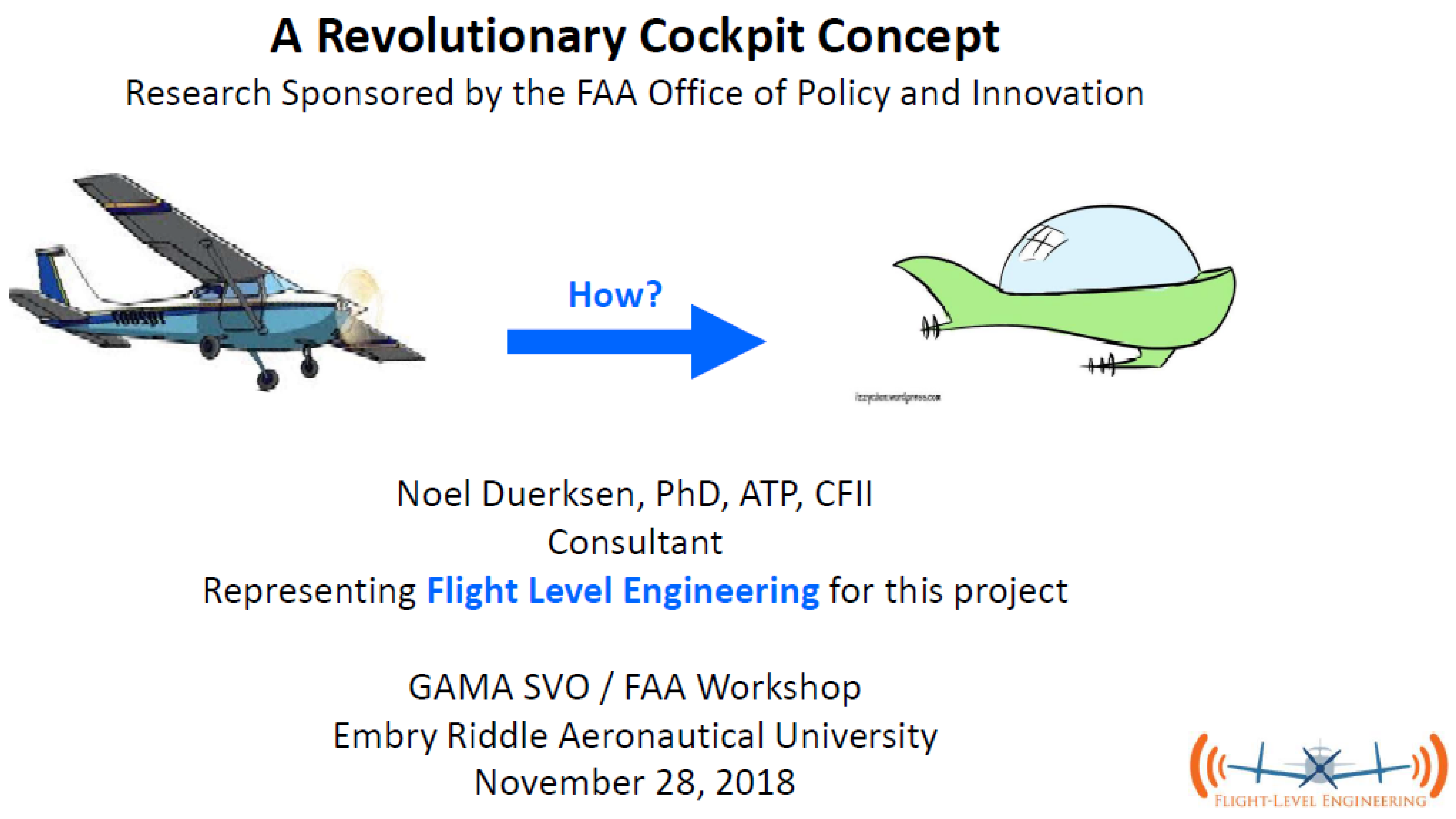


Figure 6. AGATE Bonanza and cockpit

B Appendix B: November 2018 GAMA presentation



A Revolutionary Cockpit Concept

Research Sponsored by the FAA Office of Policy and Innovation

Noel Duerksen, PhD, ATP, CFII
Consultant
Representing **Flight Level Engineering** for this project

GAMA SVO / FAA Workshop
Embry Riddle Aeronautical University
November 28, 2018

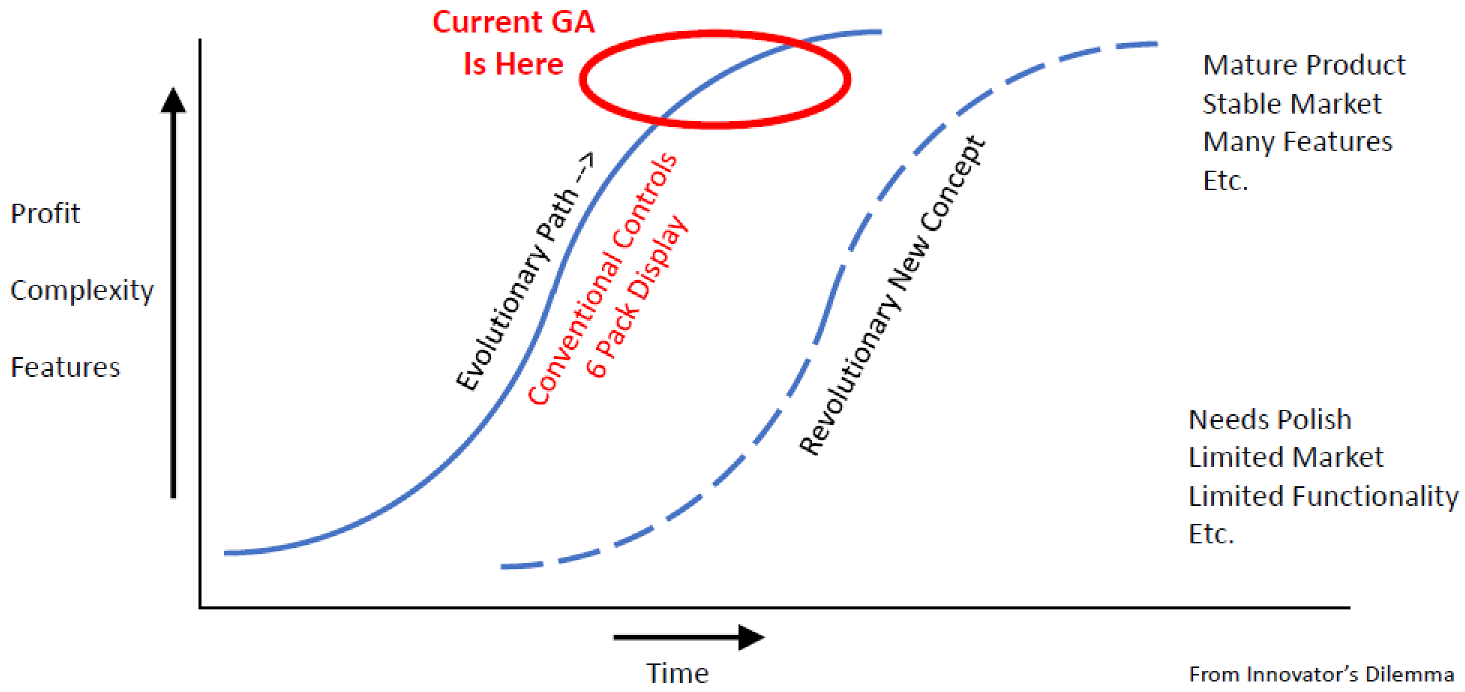
Past Successes with Innovative Government / Industry Collaboration

- AGATE
  - Composite Materials Certification Process
    - Cirrus Certified SR20 Structure
  - Reliability and Display - AC 23.1309 & AC 23.1311
    - Avidyne Developed and Certified Synthetic Vision
    - Garmin Developed and Certified Synthetic Vision then brought FAR 25 capability to FAR 23 aircraft

- Non-TSO autopilots in older certified airplanes
  - Between Dynon, TruTrak, Trio, Garmin, Genesys and others, most popular older airplanes have (or soon will have) an STC to install a low cost non-TSO'd autopilot

- 14 CFR Part 23 amendment 64 (new part 23 rewrite)
  - Eliminates many design requirements and replaces them with performance requirements (what the airplane must do, not how it must do it)

Lifecycle of a Product, Company, Business Model, Etc.



From Innovator's Dilemma
By Clayton Christensen

Current State of General Aviation

- Air Carrier fatal accident rate from all causes: 0.06 per million flights
- General Aviation fatal accident rate from pilot error only: 7.8 per million flights
  - GA pilots need assistance to improve safety – automation can help

- It takes $27,000 - $70,000* and 1 ½ years to learn to fly a GA airplane safely as a transportation machine (private & instrument)
  - The barrier to learning to fly safely is too high – automation can help

- Sophisticated FMS systems coupled to sophisticated autopilots
- Powerful automation that is different for different aircraft and is difficult to learn
- Mode confusion
  - Get rid of the baggage from legacy systems, simplify and standardize the automation

*Aspen Flying Club & Embry Riddle 2018 websites respectively

The Result of Our Current Path

All Pilots (Pvt, Com, ATP)
1997 to 2017: 19% decline

ATP
1997 to 2017: 22% increase

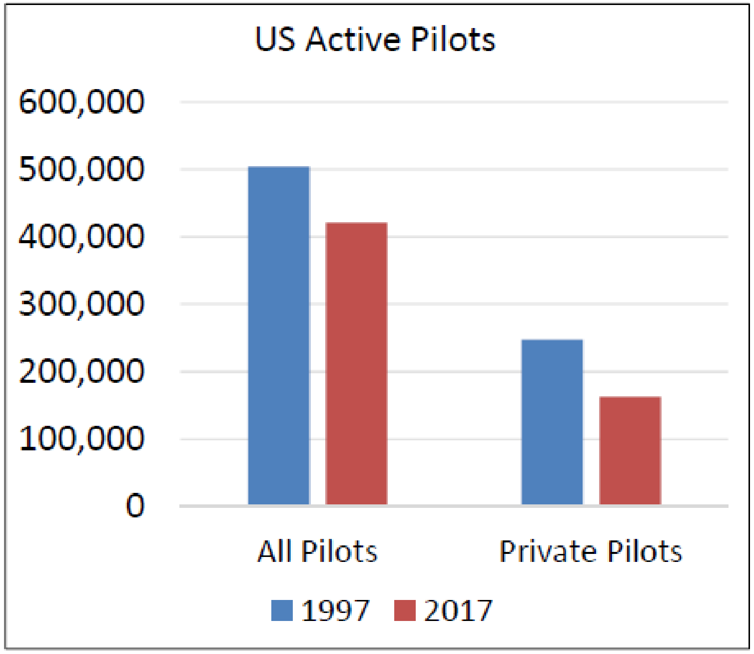
Private Pilots
1997 to 2017: 34% decline

The private pilot rate of decline is accelerating

Most of The Pilot Decline is in General Aviation

Dropout rate for student pilots is as high as 80 percent.

Private pilots drive GA market growth. They use aircraft as a tool to run their business.



Source: GAMA 2017 Databook (pilot population) & AOPA's Growing the Pilot Population Initiatives (drop out rate)

Cockpit Design Philosophy

When the computer fails, give control to the pilot.

Just get me there quickly and safely.

Cockpit Designers
(& Public?)

Rodger Ramjet

Design Assumes
A Skilled Pilot

Nintendo Kid

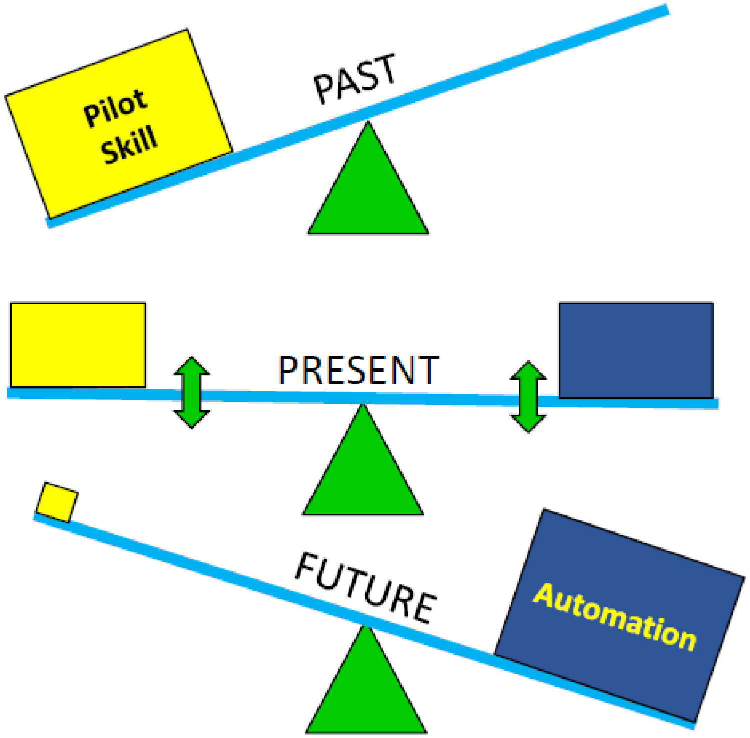
Design Assumes
Reliable Automation

Prediction: The Kids Will Outlast Us and Take Over

When the computer fails, give control to the pilot.

Rodger Ramjet

Design for
Current Skilled Pilots

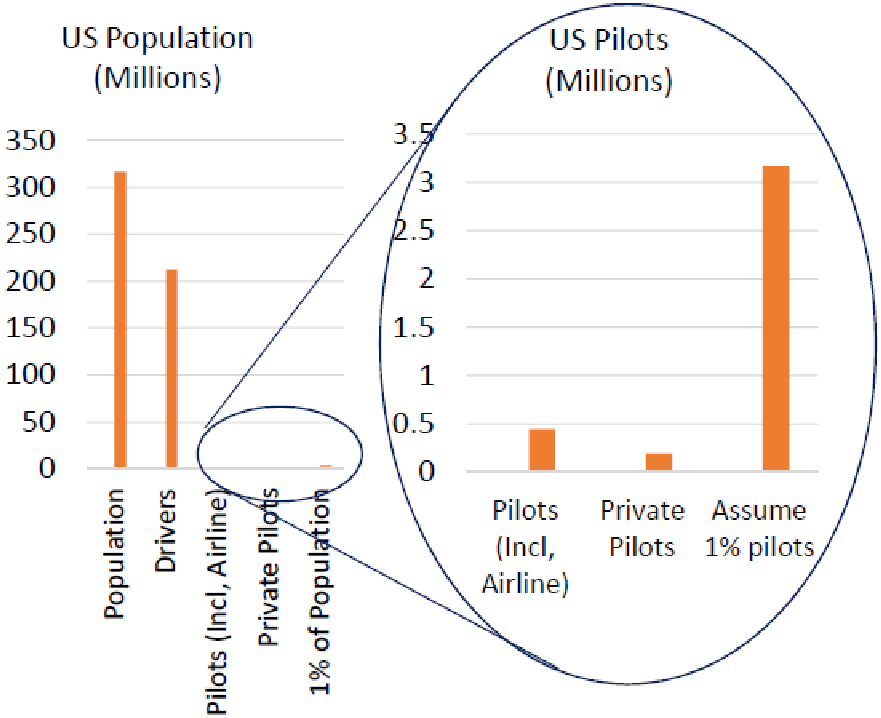


Just get me there quickly and safely.

Nintendo Kid

Design for
Future Cockpit Users

We Are Clearly Not at Our Potential
But What If . . . We Changed Course



US population that are pilots (2017):
All pilots: 0.14%
Private & Commercial pilots: 0.09%
Driver's License: 67.1%

Private & Commercial pilots represent the potential market size.

If we increase the pilot population to 1% of the US population, we increase the pilot pool (and market) by a factor of 10.

What if we invite Nintendo Kid to help design our cockpits?

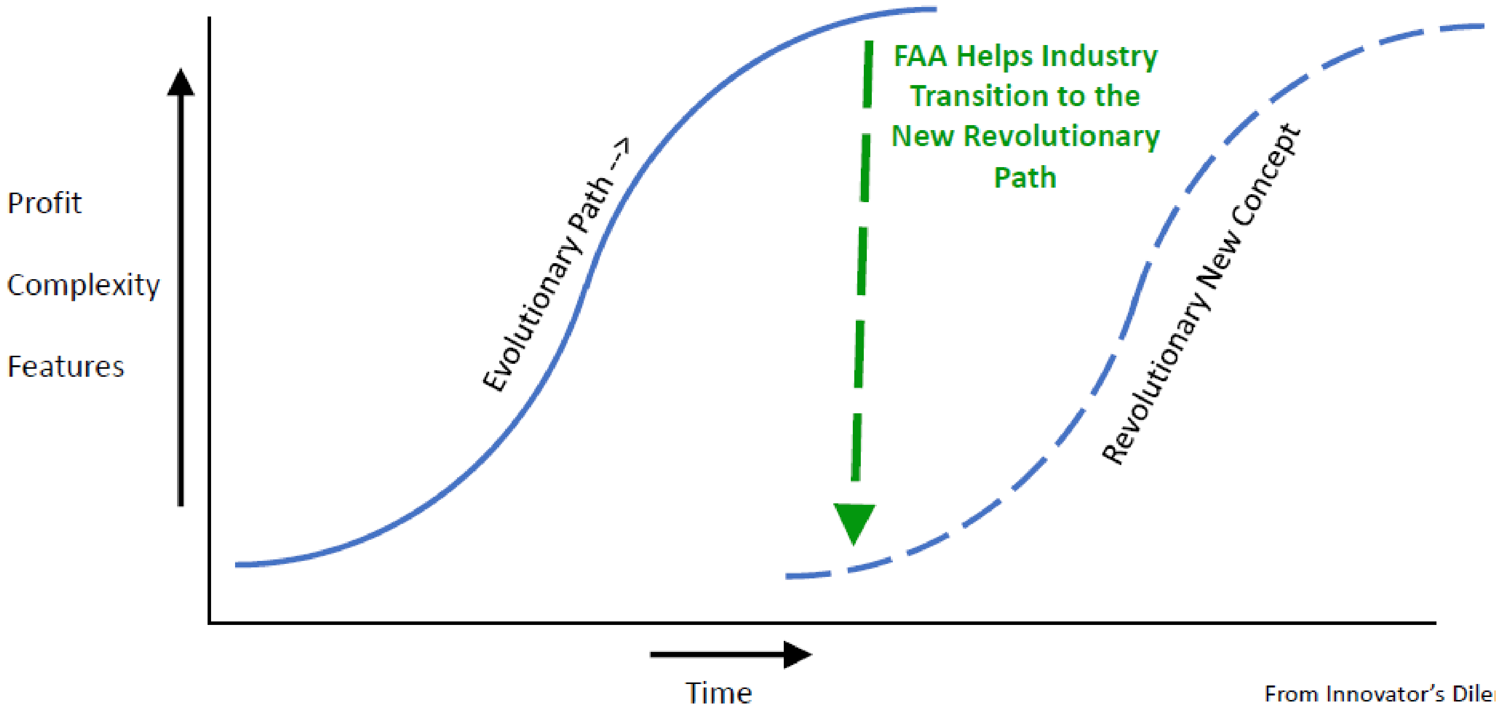
FAA Vision to Enable the New Revolutionary Path

- The Policy and Innovation Division of the FAA recognized that we cannot continue on the current evolutionary path that we have been on – we need to develop a parallel revolutionary path.

- Wes Ryan, Dave Sizoo, Ross Schaller and Bob McGuire had the foresight to develop this research project to explore safety and accessibility improvements, and then develop a way to certify these revolutionary concepts.

- While there are many aspects of this potential revolutionary path, this presentation focuses on a specific research project – maturing a simplified control system that improves safety and accessibility to the point where Means Of Compliance can be developed.

Lifecycle of a Product, Company, Business Model, Etc.



From Innovator's Dilemma
By Clayton Christensen

The Research Tools

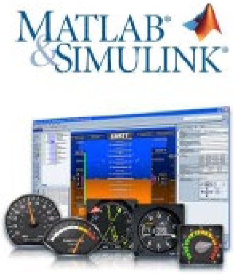
by

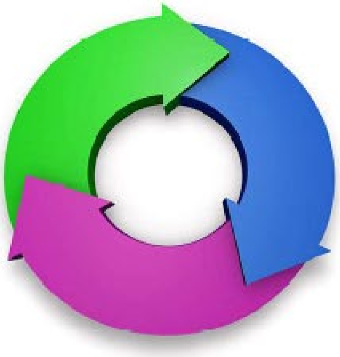
Borja Martos, PhD, ATP, CFI-AMI

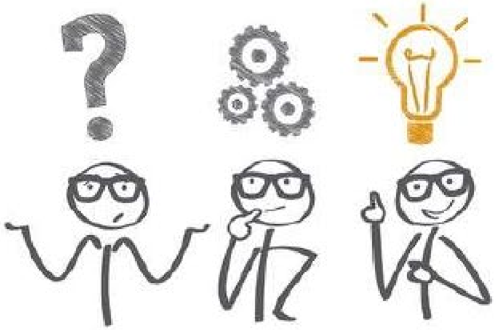
President – Flight Level Engineering LLC

Flight Level Engineering – FBW TESTBED

Copyright 1995, Frank Hlavacek







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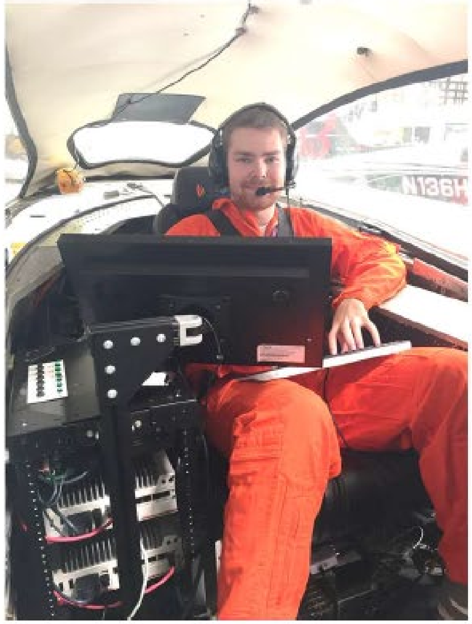
In-Flight Examples



Let’s role play thorough a few examples in-flight

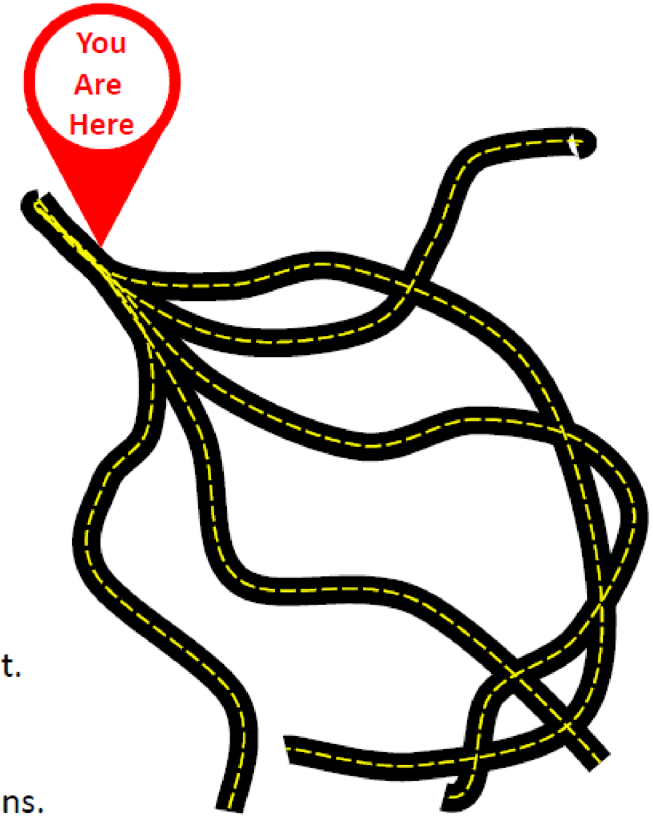
BACK TO THE FUTURE

THE FUTURE IS HERE

FLE owns and operates the next generation low cost VTOL simulation FBW testbed

Back to Noel

Research Starting Point



What is an aircraft used for?

- To go from here to there.
- Some maneuvering.

What does the pilot need to control?

- Where he is going long term (the destination).
- Where he is going short term (avoid the thunderstorm).

What features need to be included for safety purposes?

- Can't damage the aircraft by misusing the controls.
- Pilot can't be required to provide stability.
- Can't stall the aircraft.
- Pilot error (or intentional acts) cannot cause a fatal accident.

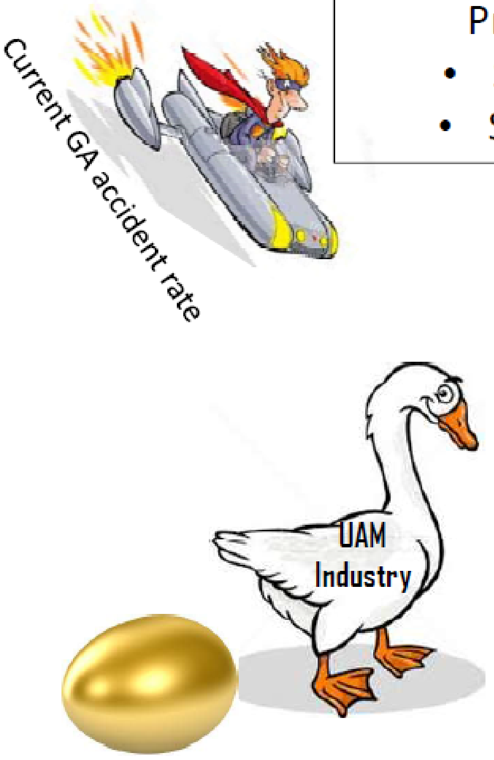
Assumptions

- Not constrained by past technology, paradigms or regulations.
- Assume low cost sensors, computers and actuators as required.

Special Needs of the Future UAM Market

Protection from Pilot Error

- Safety for the Flying Public
- Safety for non Flying Public



← or →

The General Public Won't Allow UAM if There Are Reports of Vehicles Falling on Innocent Bystanders

Design Goals

Much better safety.

- Eliminate Loss of Control Accidents
- Eliminate Controlled Flight Into Terrain accidents
- Be aware: – The automation may create new types of accidents

Much better accessibility

- Reduce pilot workload
- Reduce training and proficiency requirements

Enable the UAM Industry

- Solve pilot shortage problem
- Allow this new industry to be accepted by people on the ground

Move towards full automation

This Project Takes Us Here

And Provides the Path to Here

- Pilot can control flight path
- Pilot makes strategic decisions
- Pilot can override automation -> Automation can override the pilot -> Full automation

The Control System That Was Chosen / Developed

Velocity vector command system similar to EZ-Fly from NASA Langley

- Modified to incorporate protections
  - AOA
  - Bank
  - Pitch
  - Speed
  - G loading
  - Terrain

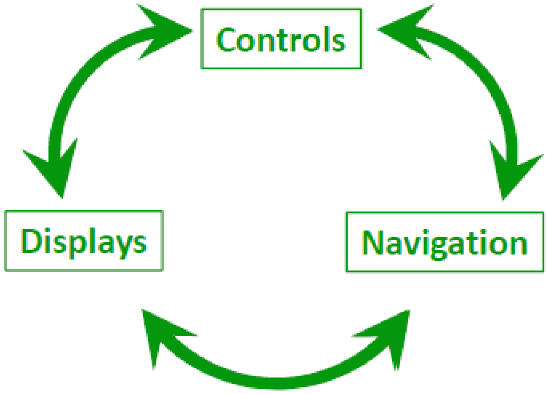
- Protections incorporated so as to operate together and seamlessly – not like a pusher

What Flight Test Research Showed

1. Flying this system with conventional glass cockpit showed that a new display concept was required to go along with the control system.

2. As a new display was developed, it became clear that a navigation system needs to be integrated with the display and controls.

3. As the navigation system was developed, it became clear that these three elements (controls, display, navigation) needed to be integrated which meant that any of the three could change the design of the other two.



Controls

Displays

Navigation

FLIGHT LEVEL ENGINEERING

EZ-Fly

Flight Path Centric Velocity Vector Command System

Two Recent SVO User Experiences:

Several Examples of

Zero Pilot Experience

17 Year Old Nintendo Kid

Zero Pilot Video Game Experience

Some Revolutionary Characteristics of the System – Need new MOCs for These

There is no attitude indicator.
    The flight controls take care of attitude.

There is no flight director to show what attitude to fly.
    The airplane is following the flight path marker or the flight plan – the pilot doesn't control attitude.

There is no trend indication of airspeed or altitude.
    The control system takes care of altitude and airspeed management.
    There is a digital airspeed and altitude display – ATC sometimes asks what your speed or altitude is.

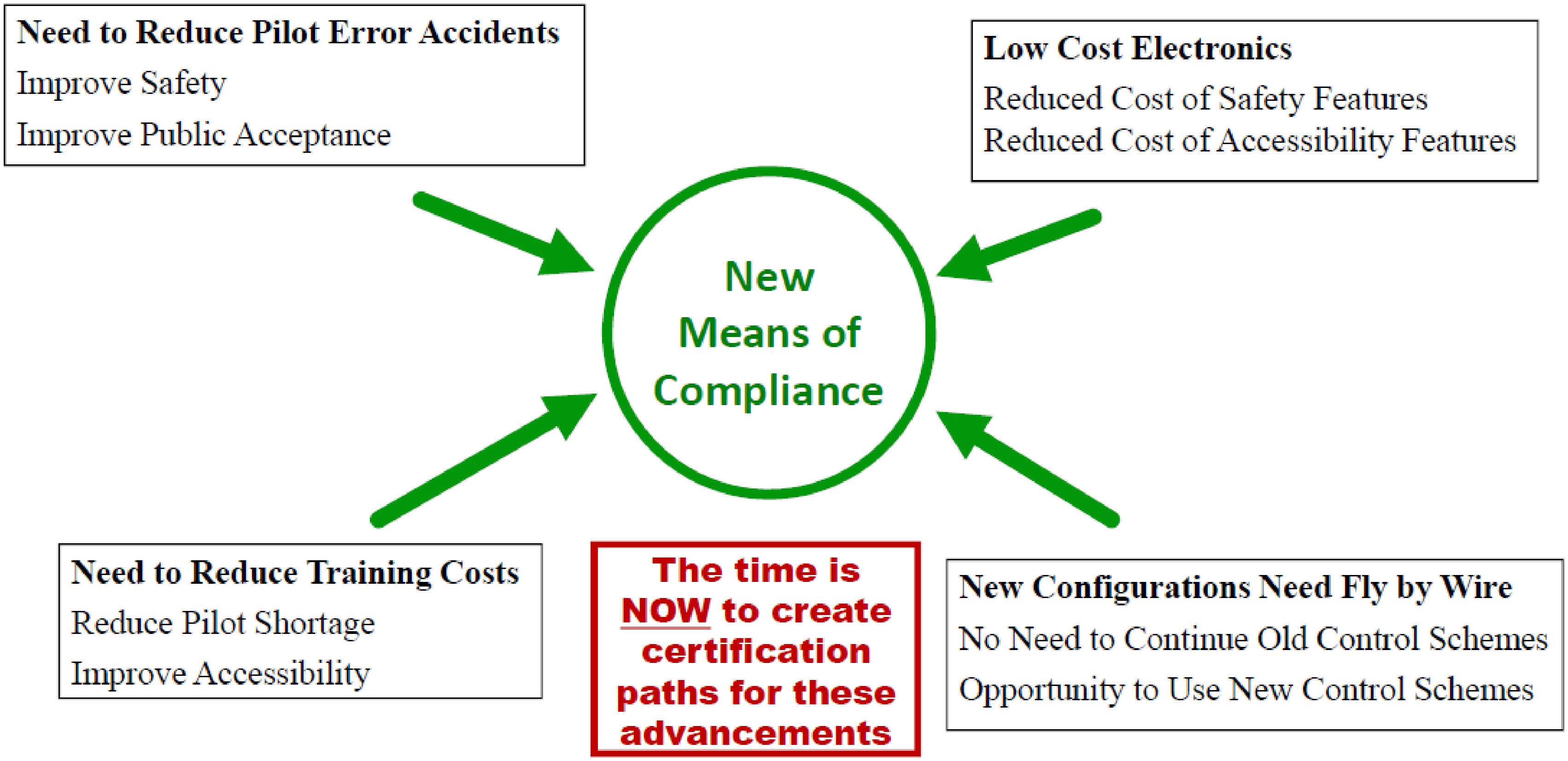
The pilot cannot go slower than approach speed with less than full power.
    At full power, the airplane will slow to no less than maximum climb speed.
    There is no stall speed.

There are no lateral or vertical deviation indictors.
    The flight controls follow the desired track.

There is no autopilot mode control panel or mode annunciation panel.
    There is no autopilot.
    The pilot does not select modes.

There is no mechanical backup or "direct" mode.

Convergence of Needs and Capabilities



Need to Reduce Pilot Error Accidents

Improve Safety

Improve Public Acceptance

Low Cost Electronics

Reduced Cost of Safety Features

Reduced Cost of Accessibility Features

New Means of Compliance

Need to Reduce Training Costs

Reduce Pilot Shortage

Improve Accessibility

The time is NOW to create certification paths for these advancements

New Configurations Need Fly by Wire

No Need to Continue Old Control Schemes

Opportunity to Use New Control Schemes

Conclusion

New configurations that require Fly by Wire, emerging UAM industry along with lower cost electronics provides both the pressure and the opportunity to dramatically improve accessibility and safety for GA.

- Workload reduction
- Prevent pilot error

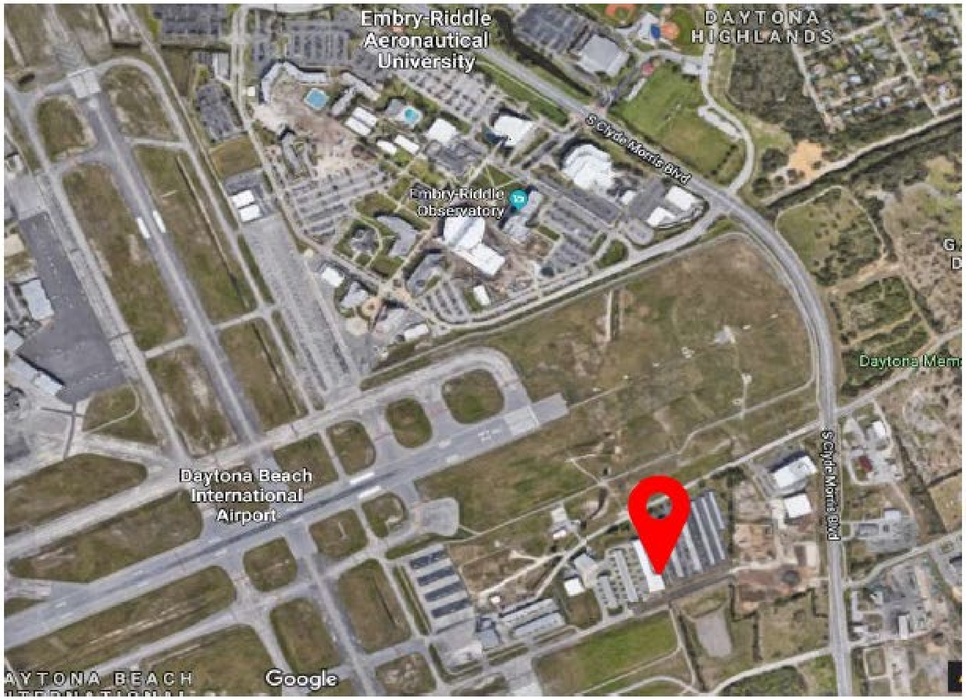
Need research to finish the SVO aircraft concept and develop ways to certify it.

- Develop rules for takeoff & landing, and automated landing approaches
- ATC
- Systems emergencies
- VTOL

Need to match training and pilot cert requirements to revolutionary technology.

EZ-FLY INFORMATION SESSSION / AIRCRAFT TOUR

0900-1200 THURSDAY



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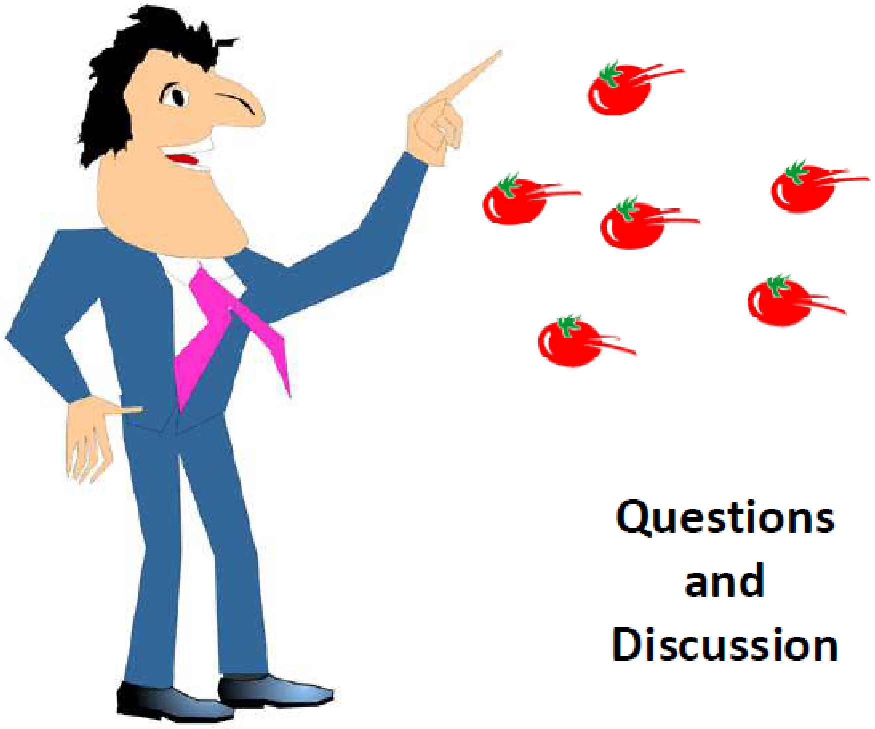

Questions
and
Discussion