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16. Abstract This report examines general aviation (GA) accident prevention strategies using automatic flight controls for basic flight envelope protection. While previous research in this area has successfully demonstrated simplified flight controls and light aircraft envelope protection, the research has failed to show a clear roadmap to certification and implementation. Previous control systems generally require fly-by-wire capability, which is prohibitively expensive for aircraft traditionally equipped with cable-actuated, reversible controls. Rather than resort to fly-by-wire systems, methods are investigated to leverage existing sensor and actuator technology to implement automatic envelope protection devices in a cost-effective manner, suitable for retrofit into the existing light-aircraft fleet. Systems that are purely advisory in nature, as well as those involving active manipulation of control surfaces, are considered. One innovation shows particular promise for providing stability augmentation and envelope protection without resorting to a fly-by-wire approach. Referred to as Force Gradient Control, the concept hinges on a new type of servo actuator that can be easily and continuously back-driven by a pilot while providing a variable torque output. The servo can provide artificial stability to the aircraft using actuation torques that are on the same order as the aircraft's natural hinge moments so that the applied forces are not objectionable to the pilot. Additionally, the same actuator can apply high torques when needed to support envelope protection schemes when the aircraft nears critical regions of the flight envelope.					
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LIST OF ACRONYMS

AC	Advisory Circular
ADAHRS	Air Data Attitude and Heading Reference System
AGATE	Advanced General Aviation Technology Experiments
AHRS	Attitude and Heading Reference System
AOA	Angle of attack
BNK	Bank
CFR	Code of Federal Regulations
DC	Direct current
DG	Directional gyro
EMF	Electro-motive force
EV	Envelope
FAA	Federal Aviation Administration
FSDO	Flight Standards District Office
GA	General Aviation
GPS	Global Positioning System
NASA	National Aeronautics and Space Administration
OEM	Original equipment manufacturer
PCH	Pitch
PI	Proportional + Integral (feedback control)
PID	Proportional + Integral + Derivative (feedback control)
PMA	Parts Manufacturer Approval
SATS	Small Aircraft Transportation System
STC	Supplemental Type Certificate
TSO	Technical Standard Order
VOR	VHF Omnidirectional Radio beacon
VOR/LOC	VOR/Localizer

EXECUTIVE SUMMARY

Light general aviation (GA) aircraft have experienced a revolution in avionics capability since the mid-1990s. Avionics has evolved from electromechanical instruments and analog radios to digital avionics that provide navigation, communication, primary flight instruments, and engine monitoring all within a few integrated flat-panel cockpit display units. These technologies enhance safety by providing better information, reducing pilot workload, and simplifying navigation procedures.

While these technologies have benefited overall situational awareness, they do not explicitly address aircraft loss of control, which remains a significant contributor to fatal accidents. Loss of control may occur as a result of disorientation during operation in Instrument Meteorological Conditions, during low-speed operation in the pattern due to an uncoordinated stall and subsequent spin, or as a result of other conditions in flight. Loss-of-control accidents account for roughly 38% of all GA aircraft accidents, or about 100 accidents and 185 lives lost each year.

To reduce loss-of-control accidents, previous research programs have sought to simplify the task of flying the airplane through some form of advanced flight control. Several successful control systems have been developed and demonstrated in flight; however, these efforts have not yet achieved a comprehensive solution to loss of control that includes a clear roadmap to the certification and implementation of such systems. Complete implementation of these solutions would likely require full fly-by-wire control, making hardware and certification costs impractical for light aircraft, which are typically controlled with cable and pulley actuation. Fly-by-wire would be especially ill-suited for retrofit into existing older aircraft, which constitute the vast majority of the GA fleet in the U.S.

There is a precedent for very limited forms of envelope protection in light aircraft. All Title 14 Code of Federal Regulations (CFR) Part 23 aircraft must have a stall warning (14 CFR 23.207), which is an advisory-only envelope protection. Of even greater significance are stall barrier systems (“stick pushers”), which are implemented on certain high-performance aircraft. These devices, covered under 14 CFR 23.691, are designed to provide a pitch motion that is equivalent to that experienced during stalls of airplanes that naturally meet the stall requirements. Of particular significance is the fact that these artificial barrier devices are automatically activated when certain criteria are met and directly manipulate a flight control against the actions of the pilot. 14 CFR 23.691 even identifies the usage of the autopilot pitch servo as a means to accomplish this action. Therefore, there is a regulatory precedent for an autopilot system providing envelope protection for light aircraft.

Using these precedents, the concepts of stall warning and stick pusher systems are expanded by leveraging the capabilities afforded by modern microprocessor and solid-state sensor packages. Several concepts for light aircraft envelope protection are developed. At a minimal level of sophistication, an advisory-only system can complement existing stall warning devices and make developing hazardous flight conditions more readily apparent to the pilot. At the higher level,

sophisticated autopilots that have envelope protection built in as a standard feature are considered. One innovation, referred to as Force Gradient Control, would enable full-time stability augmentation and envelope protection in cable-controlled aircraft without resorting to fly-by-wire control design.

1. INTRODUCTION.

1.1 BACKGROUND.

For over 10 years, National Aeronautics and Space Administration (NASA) and the Federal Aviation Administration (FAA) have collaborated on research targeted at improving general aviation (GA) safety. Examples include the Advanced General Aviation Transport Experiments (AGATE) and the Small Aircraft Transportation System (SATS) programs.

The AGATE consortium was created by NASA in 1994 to help stem the gradual decline of GA in this country. The AGATE Consortium consisted of approximately 70 U.S. aviation-related organizations and companies, including NASA, the FAA, private industry, academia, and nonprofit organizations, all striving to reverse the negative trends. GA, which includes all flying except the military services and commercial airlines, had fallen from its position of economic prominence in the late 1970s to record lows. American GA aircraft production declined from nearly 18,000 in 1978 to 954 as recently as 1993 [1]. The average GA aircraft flying was about 30 years old, often with flight deck technologies from the 1950s, and piston propulsion technologies essentially unchanged since the 1930s. Regulatory restrictions and liability claims had also taken their toll, driving up prices and causing some businesses to file for bankruptcy. American GA manufacturers spent \$3 billion between 1980 and 1994 on product liability claims alone [1].

To reverse the decline, the AGATE program focused on the development of new GA technologies, including bad weather flight and landing systems, complete with graphic displays of weather and guidance information; emergency coping and avoidance measures that use onboard systems to support decision-making; traffic avoidance systems; systems that reduce the flight planning workload and enhance passenger safety; and systems designed to improve passenger comfort, aircraft performance, and efficiency. Many different projects within AGATE explored a variety of technologies, including solid-state attitude determination using low-cost components, satellite weather, Automatic Dependent Surveillance—Broadcast transponders and onboard traffic displays, simplified flight controls, advanced flight planning and navigation systems (e.g., moving maps and highway-in-the-sky routing), affordable displays for use as primary flight display and multifunction display units, Full Authority Digital Engine Control (FADEC), diesel engine technologies, and electrostatic deicing technologies [1].

Development of the advanced displays, digital Attitude Heading Reference Systems (AHRS), and global positioning system (GPS)-based navigation that are now common in GA was encouraged by those research programs. These technologies have enhanced safety by providing better information in the cockpit and have simplified navigation procedures.

The SATS program, which was the follow-on to the AGATE program, shifted from a vehicle system focus to an overall GA transportation system focus. To relieve congested interstate highways and hub-and-spoke airports, SATS envisioned an on-demand, point-to-point, widely distributed transportation system. The concept relied on advanced 4- to 10-passenger aircraft using new operating capabilities that could leverage the nation's 5400 public-use-landing

facilities that are currently underutilized. About 98% of the U.S. population lives within 20 miles of at least one of these airports [2].

To meet these objectives, the SATS program focused on four operating capabilities:

- High-volume operations at airports without control towers or terminal radar facilities
- Technologies enabling safe landings at more airports in almost all weather conditions
- Integration of SATS aircraft into a higher-capacity air traffic control system with complex flows and slower aircraft
- Improved single-pilot ability to function competently in evolving, complex national airspace [2]

While these technologies have benefited GA, they have not addressed a key safety issue identified by AGATE and SATS: The need to simplify the task of flying and controlling the airplane in order to reduce the incidence of loss-of-control accidents. Loss of control may occur as a result of disorientation during operation in Instrument Meteorological Conditions (IMC), during low-speed operation in the pattern due to an uncoordinated stall and subsequent spin, or as a result of other conditions in flight. Loss-of-control accidents account for approximately 38% of all fatal GA aircraft accidents, or about 100 accidents and 185 lives lost each year [3].

The U.S. government has supported research to investigate simplified flight controls, and sophisticated control laws have been developed [4]. The research has failed, as of yet, to show a clear roadmap to the certification and implementation of such systems. Full implementation would likely require full fly-by-wire control systems, which is unusual in the GA community. Even new production, multimillion dollar aircraft with weights in excess of 12,000 lb (e.g., Beech King Air) still use mechanical control systems because of their simplicity and reliability.

Because of the effort and expense that such systems require, conventional wisdom has been that envelope protection schemes are too expensive for inclusion in light aircraft designs. However, there are several misconceptions that lead to such a conclusion. The first misconception is that envelope protection, necessarily, has to involve complex flight control schemes necessitating the use of fly-by-wire hardware. The second misconception is that there is no real precedent for such systems in light aircraft, and therefore, no regulatory basis for certification.

However, all aircraft certificated under Title 14 Code of Federal Regulations (CFR) Part 23 must have a stall warning (14 CFR 23.207), which is an advisory-only type of envelope protection. Of even greater significance are stall barrier systems (“stick pushers”), which are implemented on certain high-performance aircraft that cannot meet the stall requirements of 14 CFR 23.201 through aerodynamic design alone. These devices, covered under 14 CFR 23.691, are designed to provide a pitch motion that is equivalent to that experienced during stalls of airplanes that naturally meet the stall requirements. Of particular significance is the fact that these artificial barrier devices are automatically activated when certain criteria are met and directly manipulate a flight control against the actions of the pilot. 14 CFR 23.691 even identifies the usage of the

autopilot pitch servo as a means to accomplish this action. Therefore, there is a regulatory precedent for an autopilot system providing envelope protection for light aircraft.

In the research reported here, the basic concepts of stall warning and stick pusher systems have been expanded in consideration of the capabilities afforded by modern microprocessors, solid-state sensor packages, and advanced actuators. Several concepts for light aircraft envelope protection have been developed. At the lowest level of sophistication, advisory-only systems that can complement existing stall warning devices and make developing hazardous flight conditions more readily apparent to the pilot are described. At the higher level, sophisticated autopilots that have envelope protection built in as a standard feature are considered. One innovation, referred to as Force Gradient Control, shows particular promise. The concept enables stability augmentation and full envelope protection on a cable-controlled aircraft, without resorting to fly-by-wire control design.

1.2 FLY-BY-WIRE SYSTEMS.

Fly-by-wire systems have the technical advantage of providing complete freedom to tailor the response of the aircraft control surfaces to pilot inputs. GA aircraft, with their cable-actuated control surfaces are limited in that the autopilot actuator and the pilot act on the same cable. There is no summing of signals or intrinsic mechanism for implementing pilot-in-the-loop stability augmentation. However, due to the reliability and economy of cable-actuated systems, it is difficult to justify replacing them with fly-by-wire systems.

Consider the benefits of cable systems:

- Failure resistant—The strong steel cable is unlikely to break. Frozen pulleys and broken fixtures do not cause system failure.
- Easy maintenance—Cable, pulleys, and fixtures can be easily inspected visually and parts are inexpensive.
- No power required—No power is required to activate surfaces. Surfaces work even with total engine and electrical failures.
- Proper stick force gradients—The loading on the control surfaces is automatically routed back to the control yoke giving the pilot the required tactile feedback.

From the standpoint of aircraft infrastructure, the electrical systems present in the majority of the light GA fleet are inadequate to support fly-by-wire systems. Most light aircraft have a direct current (DC) (12V or 24V) power system with only a battery, alternator, and a primitive bus. Total electrical failure is possible through single-point failures. A failed solenoid (master or even starter solenoid) can easily result in system failure. Power buses often consist of a hot strip of aluminum sheet metal to which all system circuit breakers are connected. The bus can be easily grounded by an accident, resulting in a system failure.

While fly-by-wire systems have the technical advantage of providing complete freedom to tailor the response of the aircraft control surfaces to pilot inputs, this freedom has potential downsides, and it can be argued that the misuse of this flexibility has led directly to accidents in transport category airplanes. The burden of designing and proving that fly-by-wire control systems cannot have unintended adverse safety consequences is significant. The associated costs must be justified by performance or safety enhancements in order for such systems to be economical.

Given the desire to remain affordable for owners, it is difficult to imagine retrofitting existing light GA aircraft with a fly-by-wire system. With this in mind, the focus of this work has been directed toward advisory systems and mid-level control solutions that can be embedded into retrofit autopilot systems. Fly-by-wire systems may have a future in GA, but it is likely to be a forward-fit solution for future generations of new aircraft designs.

1.3 ENVELOPE PROTECTION SCOPE.

Before introducing potential concepts for envelope protection, it is important to define for the purpose of this effort what envelope protection is and what it is not. Table 1 identifies a number of common accident types, their initiating control error, and the corresponding corrective action required to avoid them. The accident types listed can be categorized according to whether they could be prevented by an envelope protection system or a flight monitor system. An envelope protection system guards against excessive deviations of aircraft state, whereas flight monitor system provides anticipatory guidance to the pilot of impending hazardous situations. Envelope protection may be thought of as tactical in nature, whereas flight monitor is strategic. For instance, envelope protection guards against exceeding certain basic flight envelope limits that are instantaneous and easily detected using relatively simple sensors (e.g., airspeed, angle of attack (AOA)). A flight monitor system, in contrast, would detect evolving higher-level threats that require more sophistication and situational awareness to identify.

Table 1. General Aviation Accident Types, Initiating Causes and Correcting Actions

Accident Type	Initiating Cause(s)	Correcting Action(s)	Envelope Protection Related?	Flight Monitor Related?
Stall-spin	Poor coordination during slow flight	Center the ball, decrease AOA, add power	Yes	No
Accelerated stall	Exceeding critical AOA during maneuver	Relax back pressure on yoke	Yes	No
Overspeed/ structural failure	Poor speed/ attitude control	Maintain speed/attitude within acceptable bounds	Yes	No
Unusual attitude with subsequent loss of control	Poor attitude control (multiple contributing circumstances)	Maintain attitude within acceptable bounds	Yes	No
Stall-fall	Poor energy management/ bad flair to land	Proper airspeed control, flare at proper altitude, power addition	Partially	Yes
Insufficient altitude for dive recovery	Poor altitude planning	Start pullout earlier	Partially	Yes

Table 1. General Aviation Accident Types, Initiating Causes and Correcting Actions
(Continued)

Accident Type	Initiating Cause(s)	Correcting Action(s)	Envelope Protection Related?	Flight Monitor Related?
Controlled flight into terrain	Poor choice of altitude/ terrain awareness	Alter path and altitude as needed to avoid terrain	No	Yes
Severe weather penetration	Poor flight planning. Failure to detect severe weather	Circumnavigate weather cells	No	Yes
Runway loss of control	Complex causality	Complex: requires multiple actions to maintain directional control	No	Maybe
Icing-related mishaps	Inadequate weather avoidance and inadequate airframe protection	Avoid icing conditions; mitigate encounters with TKST™ or other systems; exit icing conditions as soon as possible	No	Yes
Collision with terrain following takeoff	Improper performance estimation and/or inadequate awareness of terrain	Accurately predict performance; alert pilot to dangerous situations and/or inadequate performance during departure; maintain best climb performance	No	Yes
Midair collision	Failure to see and avoid other aircraft	Evasive maneuvering	No	Yes
Fuel exhaustion	Poor fuel planning	Proper preflight planning and in-flight replanning	No	Yes
Mechanical failure	Failure to detect fault early	Early fault detection	No	Yes

TKST™ = Ice Protection Systems by CAV Aerospace, Inc.

The first three accident types in table 1 contend with exceeding a basic limit on the aircraft and are definitely within the scope of envelope protection. In the cases of stall/spin and accelerated stall, basic AOA limits are exceeded. For overspeed and airframe stress-related incidents, airspeed and g loading are exceeded, respectively. Unusual attitude leading to loss of control do not entail exceeded limits, since extreme pitch and bank angles are not inherently dangerous. However, extreme attitudes may lead to disorientation or to situations that will exceed basic limits or may cause a collision with terrain. Therefore, limiting pitch and bank angles is advisable and definitely within the scope of envelope protection, although the desired boundaries may vary with the type of operation.

The stall-fall and the dive recovery scenarios are more complex. In the stall-fall scenario, the aircraft landing flare is initiated too high above the runway, leading to a stall and a greatly increased descent rate. Proper recovery requires the addition of power and a small reduction in AOA. Detecting this scenario requires the automation to know (or infer) that a landing is taking place and that the aircraft is too high. Envelope protection would identify the stall condition, but not necessarily identify the special case of a poor landing. Such an inference is beyond the scope of simple aircraft state monitoring and would require a more sophisticated, predictive type of flight-monitoring function.

The dive recovery scenario involves an aircraft that is in an unusual attitude leading to a high descent rate. In this scenario, the pilot may have intentionally initiated a high descent rate unaware that the necessary altitude for recovery is not available. While such maneuvering is typically considered outside the bounds of a normal/utility category aircraft, it is not inconceivable that some activities (e.g., agricultural) might lead to such a scenario. The hazardous condition might be detected by envelope protection if the attitude is extreme, or the aircraft's speed is excessive. However, the exact nature of the threat (i.e., impacting the ground) would not be identified by a simple envelope protection system. Therefore, this type of scenario is within the scope of the flight-monitoring system. To detect the danger, the automation must have knowledge of the terrain elevation and be able to calculate the altitude required for recovery.

Situations involving controlled flight into terrain, weather penetration, and traffic collision avoidance have little to do with exceeding basic limits and are mostly navigational problems. In these cases, the dangerous situation is not detectable with basic instruments, but rather must rely on navigational systems and appropriate databases. These types of scenarios are within the scope of flight monitoring and not envelope protection.

Other threats, such as malfunctions and fuel exhaustion, are more appropriately categorized as flight-monitoring functions as well.

With these considerations in hand, therefore, the scope of envelope protection per se is narrowed to the following three major areas.

- Exceeding critical AOA (i.e., stall and stall/spin)
- Exceeding pitch/bank limits (i.e., unusual attitude)
- Exceeding airframe limitations (i.e., overspeed/high g loading)

It should be noted that an envelope protection system could be viewed as a precursor to, and perhaps a necessary prerequisite for, a more comprehensive flight safety protection system that includes not only envelope protection but also the flight-monitoring functions noted above.

1.4 TARGET PRODUCT AND AIRCRAFT.

In 2006, all the combined GA manufacturers shipped 2750 piston aircraft worldwide [5]. In 2006, there were 145,036 piston singles flying and 18,708 piston twins flying in the U.S. for a total of 163,744 piston aircraft [6]. Assuming that all new deliveries are absorbed into the U.S. fleet, new production aircraft comprise only 1.7% of the total aircraft in service. Therefore, to have a significant impact on GA safety within the piston fleet as a whole, at least in the span of a few years, the primary target for envelope protection must include retrofitting the existing aircraft. For this reason, a successful envelope protection product must appeal to the individual aircraft owner/operator.

Owner pilots are likely to have sufficient confidence in their own piloting skills not to perceive a need for an envelope protection tool. In some cases, large fleet owners, such as training operators, may see a benefit to equipping the aircraft to prevent incidents involving novice

pilots; but in the majority of cases, a pure envelope protection system is likely to be a difficult product to market. Envelope protection systems are likely to have much more appeal if they are incidental features to other systems that have more perceived utility. For instance, envelope protection systems may need to be embedded in highly capable autopilot systems that provide significant perceived benefits during normal aircraft operations, in order for pilot/owners to be willing to invest in their purchase and installation.

2. RETROFIT ENVELOPE PROTECTION SYSTEMS.

A family of envelope protection systems is possible for retrofit applications, with a variety of levels of sophistication.

Table 2 lists the proposed six system options with their respective capabilities indicated. System I is an advisory-only system, while the others include at least single-axis control capability. Systems II, III, and IV could be implemented without an explicit source of digital attitude information; while Systems V and VI require a digital AHRS or equivalent internal attitude estimation capability. These six systems are described in further detail in the following sections.

Table 2. Proposed Envelope Protection System Options and Their Capabilities

	Proposed System					
	I	II	III	IV	V	VI
Axes of Control	0	1	1	2	3	3
Capabilities						
Stall warning/protection	W	P	W	P	P	P
Spin warning/protection	W	W	W	W	P	P
Overspeed warning/protection	W	P	W	P	P	P
Over-g warning/protection	W	P	W	P	P	P
Overbank warning/protection			P	P	P	P
Overpitch warning/protection					P	P
Lateral autopilot			√	√	√	√
Longitudinal autopilot		√		√	√	√
Yaw damper					√	√
Autothrottle						√
Autoland						√
Estimated Mature Retail Price	\$1000	\$8000	\$8000	\$14,000	\$18,000	\$28,000

W = Warning only

P = Both warning and active protection

√ = Included

2.1 SYSTEM I: BASIC ADVISORY SYSTEM.

A functional schematic of System I is shown in figure 1.

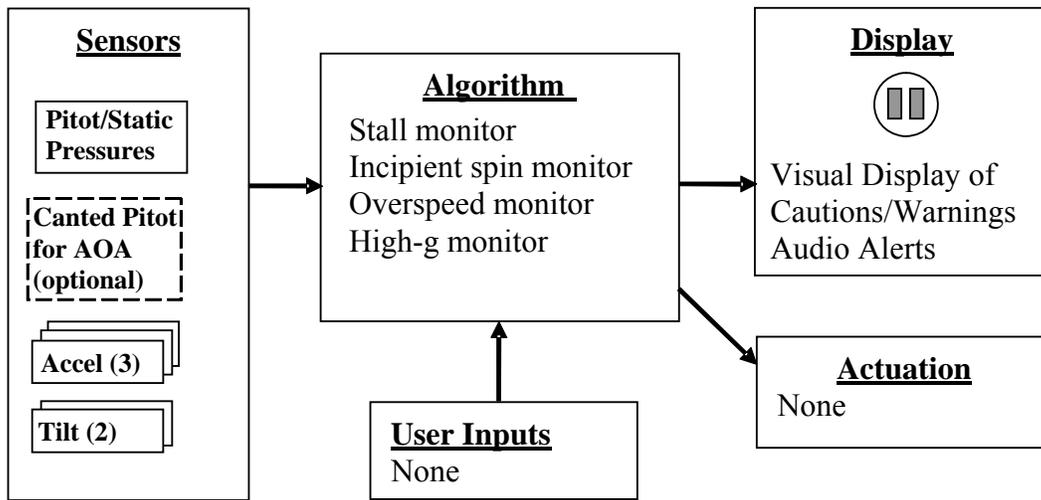


Figure 1. Basic Advisory Envelope Protection System

The Basic Advisory System has the following characteristics:

- **Sensors**—The unit includes sensors for pitot and static pressures, and potentially, a third partial-pitot pressure measurement to aid in determining AOA. Additional sensors include a three-axis accelerometer with a two-axis tilt sensor (the latter for estimating and subtracting out highly variable accelerometer biases).
- **User Inputs**—None.
- **Algorithms**—The Basic Advisory System includes algorithms to provide monitoring, caution, and warning for the following conditions: stall, incipient spin, overspeed, and excessive airframe loading (“over-g”).
- **Displays / Outputs**—The system will include simple audio alerts at a minimum, with a design option for a simple visual display.
- **Actuation**—None.

The Basic Advisory System has no control capability, serving only as a source of caution and warning information for the pilot. It can function as a legal stall warning replacement while providing additional warnings for incipient spin, overspeed, and over-g conditions.

The system uses pitot/static inputs to determine indicated airspeed, with an optional AOA sensor. It also has a three-axis accelerometer and a two-axis tilt sensor. The accelerometers are

used to measure airframe acceleration, and the tilt sensors are used to control the accelerometer bias drift.

The advantages of this advisory-only system are:

- Extremely low cost
- Economical replacement option for failed, required equipment (existing stall warning system)
- Provides previously unavailable active visual and aural warnings of incipient spin
- Includes additional warnings for overspeed and high-g conditions

2.2 SYSTEM II: VERTICAL AUTOPILOT WITH ENVELOPE PROTECTION.

A functional schematic of System II is shown in figure 2. This system is envisioned as an add-on module for retrofit into the many aircraft in the fleet that have only a lateral autopilot. Many operators of those aircraft desire vertical speed control, flight-level change, and altitude-hold capability without having to replace the existing, functional single-axis autopilot.

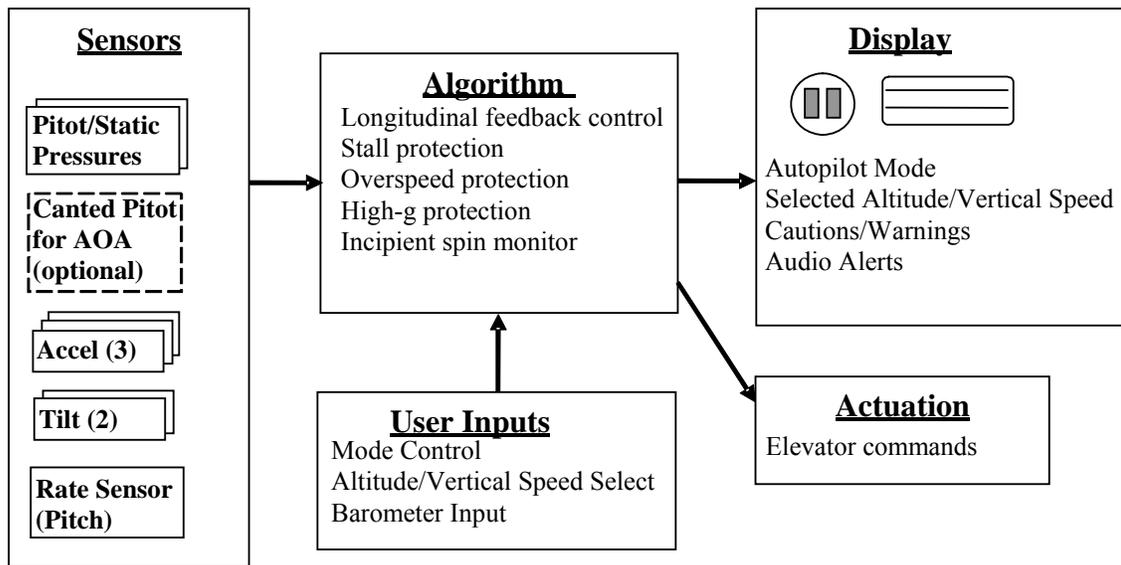


Figure 2. Longitudinal Control Module With Envelope Protection

In addition to all the features of the Basic Advisory System described in the previous section, the Vertical Autopilot With Envelope Protection has the following additional characteristics.

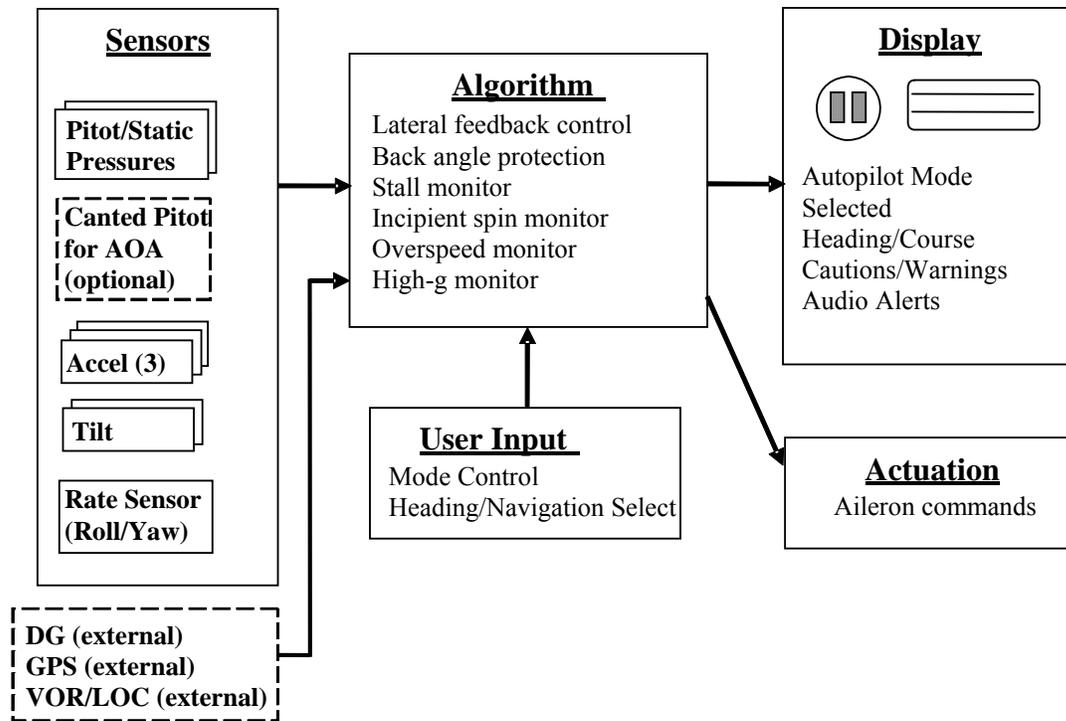
- **Sensors**—A single angular rate sensor is added to the unit to sense aircraft pitch rate. This is used to assist in faster feedback loop closure of vertical autopilot functions.
- **User Inputs**—A control or display head with user controls is required to activate the vertical autopilot functions and to choose between modes. The envelope protection features of the system are on by default, but the user may choose to disable them if desired.

To support altitude capture and altitude hold, the user will be required to enter the local altimeter setting into the unit for baro-altimeter corrections.

- **Algorithms**—In addition to the Basic Advisory System algorithms to provide cautions and warnings, the Vertical Autopilot With Envelope Protection implements vertical autopilot modes, including altitude preselect and capture, vertical speed control, and flight-level change (altitude change at constant selected airspeed). Rather than simple caution and warning for stall, overspeed, and high-g circumstances, this system adds actual envelope protection by issuing aircraft control interventions (via elevator control) to avoid or mitigate such conditions. Incipient spin protection is limited to stall protection, as there is no means to regain coordinated flight automatically in this system.
- **Displays/Outputs**—Audio and visual caution-and-warning annunciations remain as in the Basic Advisory System. In addition, audio and visual alerts are given to the pilot in an unambiguous manner to inform him/her whenever the system intervenes to actuate control in an effort to protect the aircraft. The usual mode annunciations for normal autopilot modes are also provided.
- **Actuation**—Elevator control is added to this system to effect both vertical autopilot functions and vertical envelope protection functions.

2.3 SYSTEM III: LATERAL AUTOPILOT WITH ENVELOPE PROTECTION.

A functional schematic of System III is shown in figure 3. This system is a stand-alone, single-axis autopilot. While the market for such a system may be limited, cost-conscious owners with existing single-axis autopilots that fail, or with no autopilot, may choose a new single-axis autopilot simply to obtain heading-hold and course-tracking features at an affordable price. This system is designed to provide that basic functionality, and in addition, some valuable envelope protection features.



VOR/LOC = VOR/Localizer

Figure 3. Lateral Control Module With Envelope Protection Features

In addition to all the features of the Basic Advisory System previously described, the Lateral Autopilot With Envelope Protection has the following additional characteristics.

- **Sensors**—A single angular rate sensor is added to the unit to sense a combination of aircraft roll rate and aircraft yaw rate. This rate output is used to assist in faster feedback loop closure for the autopilot’s heading-hold and course-tracking modes.

External data feeds from the exiting aircraft directional gyro (DG) and if equipped, navigational aids, including VHF omnidirectional radio beacon (VOR)/Localizer (VOR/LOC) and GPS, are required to provide the desired lateral autopilot features.

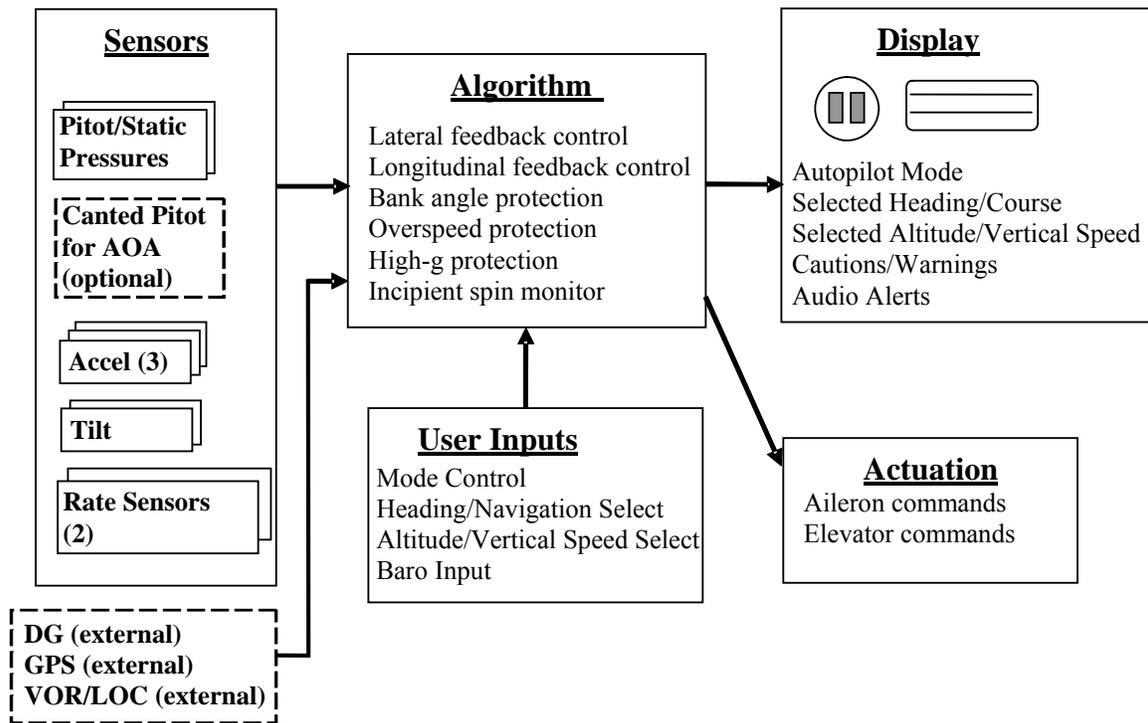
- **User Inputs**—A control or display head with user controls is required to activate the lateral autopilot functions and to choose between modes. The lateral envelope protection features of the system are on by default, but the user may choose to disable them if desired.
- **Algorithms**—In addition to the Basic Advisory System algorithms to provide cautions and warnings, the Lateral Autopilot With Envelope Protection implements lateral autopilot modes, including heading-hold; GPS steering, including procedure turns; and VOR and localizer course intercepts and tracking. In addition to the caution and warning features for stall, overspeed, and high-g circumstances, this system is able to add automatic envelope protection for excessive turn rate, which is generally well-correlated

with excessive bank angle. It is judged that the quality of lateral envelope protection would be adequate using rate information only and appropriately chosen parameters for limits on turn rate. No active control interventions for stall, stall-spin, overspeed, and over-g circumstances are possible with this lateral control only system; in these cases, only caution and warning annunciations are provided.

- Displays/Outputs—Audio and visual caution and warning annunciations remain as in the Basic Advisory System. In addition, audio and visual alerts are given to the pilot in an unambiguous manner to inform him/her whenever the system intervenes to actuate lateral control to remedy an excessive turn rate circumstance. The usual mode annunciations for normal autopilot modes are also provided.
- Actuation—Aileron control is added to this system to provide lateral autopilot functions and lateral turn rate/bank angle protection.

2.4 SYSTEM IV: TWO-AXIS AUTOPILOT WITH ENVELOPE PROTECTION.

A functional schematic of System IV is shown in figure 4. This system is a stand-alone, rate-based, two-axis autopilot, suitable for complete replacement of existing aircraft autopilots (perhaps reusing their existing servos if present and compatible) or as an economical new autopilot installation.



VOR/LOC = VOR/Localizer

Figure 4. Two-Axis Autopilot With Envelope Protection Features

This system combines all the features of System I, System II, and System III. The features of this system are described below.

- Sensors—Two angular rate sensors are included in the unit: one for aircraft pitch rate, and a second to sense a combination of aircraft roll rate and aircraft yaw rate. These rates provide for faster feedback loop closures for the vertical and lateral modes of the two-axis autopilot.

External data feeds from the existing aircraft DG and if equipped, navigational aids including VOR/LOC and GPS, are required to provide the desired lateral autopilot features.

- User Inputs—A control/display head with user controls is required to activate the autopilot functions and to choose between modes. The envelope protection features of the system are on by default, but the user may choose to disable them if desired.

In order to support altitude capture and altitude hold, the user will be required to enter the local altimeter setting into the unit for baro-altimeter corrections.

- Algorithms—This two-axis system provides all the cautions and warnings of the Basic Advisory System, plus all the autopilot functions of the Vertical and Lateral Autopilots. Active envelope protection features provide automatic control intervention to avoid stall, overspeed, and high-g circumstances; and also excessive turn rate/bank angle conditions. Active control intervention incipient stall-spin is limited to stall protection only, since there is no rudder servo to allow return to coordinated flight.
- Displays/Outputs—Audio and visual caution and warning annunciations remain as in the Basic Advisory System. In addition, audio and visual alerts are given to the pilot in an unambiguous manner to inform him/her whenever the system intervenes to actuate any of its envelope protection control interventions. The usual mode annunciations for normal autopilot modes are also provided.
- Actuation—Aileron and elevator control are provided, both for autopilot functions and for envelope protection functions.

2.5 SYSTEM V: THREE-AXIS AUTOPILOT WITH ENVELOPE PROTECTION.

A functional schematic of System V, Three-Axis Autopilot With Envelope Protection, is shown in figure 5. This system is a stand-alone, attitude-based, three-axis autopilot, suitable for complete replacement of existing aircraft autopilots (perhaps reusing their existing servos if present and compatible) or as new full-featured, high-performance autopilot installation.

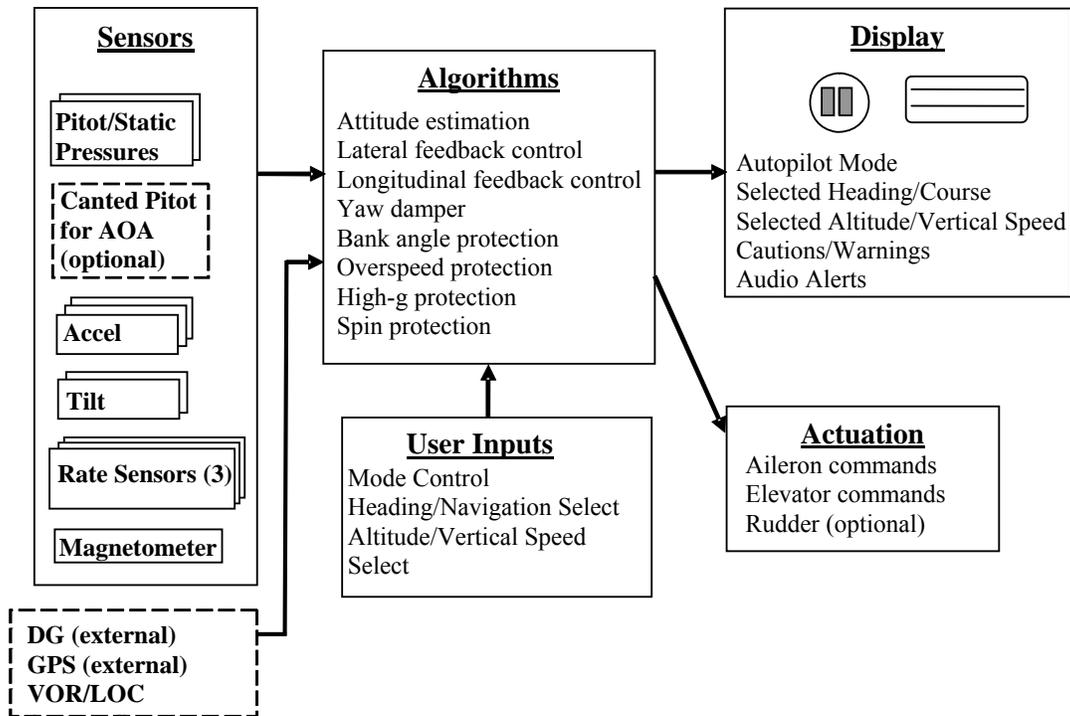


Figure 5. Three-Axis Autopilot With Envelope Protection

This system provides all the caution and warning features of System I. In addition, attitude estimation algorithms provide a built-in Air Data Attitude and Heading Reference System (ADAHRS) functionality. Alternatively, the inputs from the sensors block and the attitude estimation algorithms could be replaced by a separate, stand-alone ADAHRS plus an AOA measurement. Regardless of the source, this system benefits from the presence of full aircraft state information and, therefore, is capable of providing full three-axis autopilot features and three-axis envelope protection.

- **Sensors**—Three angular rate sensors are included to support both rate outputs and attitude estimation. In addition, a magnetometer is required for attitude and heading estimation. This magnetometer would be remote-mounted to allow a clean magnetic environment.

External data feeds from the existing aircraft DG and if equipped, navigational aids, including VOR/LOC and GPS, are required to provide the desired autopilot lateral-navigation features.

- **User Inputs**—A control or display head with user controls is required to activate the autopilot functions and to choose between modes. The envelope protection features of the system are on by default, but the user may choose to disable them if desired. In particular, for this three-axis system, to allow for deliberate uncoordinated flight in crosswind landings, the yaw-axis envelope protection functions could be overridden by pilot selection.

To support altitude capture and altitude hold, the user will be required to enter the local altimeter setting into the unit for baro-altimeter corrections.

- Algorithms—This three-axis system provides all the cautions and warnings of the Basic Advisory System, plus all the autopilot functions of the Vertical and Lateral Autopilots. Higher-precision capture and tracking is allowed by the use of attitude information. Since bank and pitch angles are available, related caution and warnings and active envelope protection (based on these states) are provided. In addition, the rudder servo in this system allows both a yaw damper and the preservation of coordinated flight in normal circumstances, plus active protection against incipient stall or spins.
- Displays/Outputs—Similar to the previously described systems, audio and visual alerts are provided, as are alerts whenever the system intervenes in any of its envelope protection control functions. Mode annunciations for autopilot modes are, of course, provided.
- Actuation—Full three-axis aileron, elevator, and rudder control are provided, both for autopilot functions and for envelope protection functions.

2.6 SYSTEM VI: INCLUSION OF AUTOTHROTTLE AND AUTOLAND.

Figure 6 shows a functional schematic of System VI.

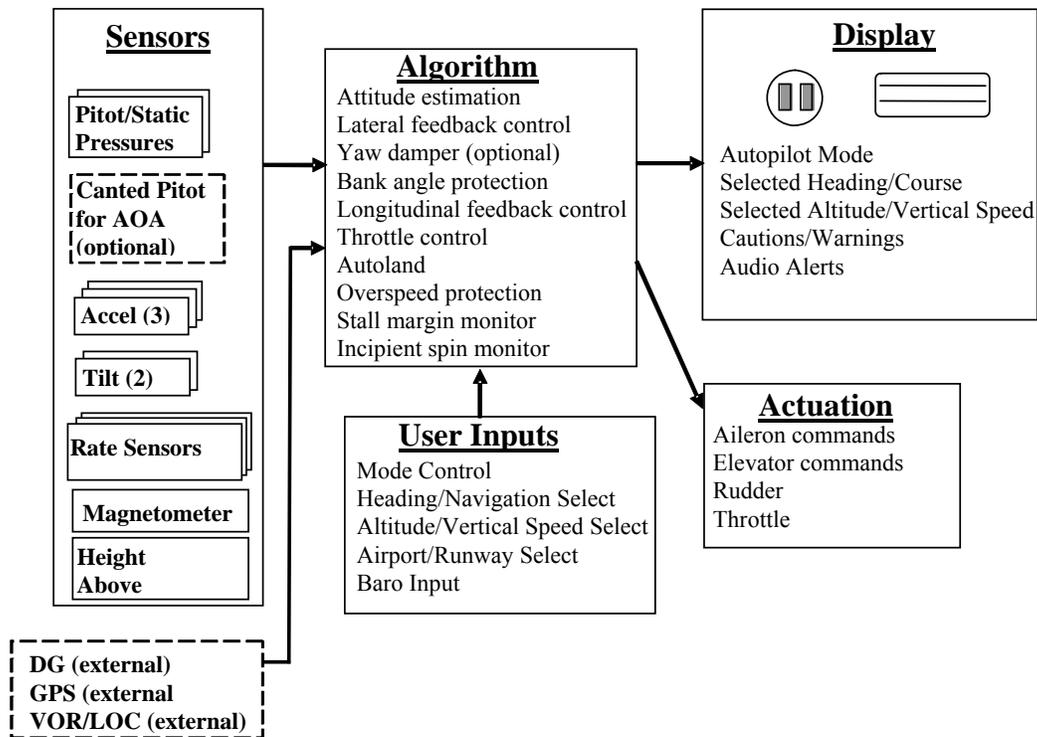


Figure 6. Three-Axis Autopilot With Added Autothrottle and Autoland Capabilities

This system is the most technologically advanced of the proposed retrofit systems for envelope protection. It encompasses all the functionalities of System V, and with the addition of a single height-above-ground sensor and a single throttle actuator, it adds the capability to do full authority vehicle control, including automated descents and landings.

- **Sensors**—In addition to the sensors required by a typical ADAHRS (internal or external to the system), this system also requires an explicit AOA measurement and a sensor to detect height-above-ground at low altitudes (30 ft or less) to support a landing flare. The height-above-ground sensor could potentially be a simple laser-based range detector, or possibly an ultrasonic range detector, rather than a radar altimeter, which would likely be more expensive.
- As in previous systems, external data feeds from the exiting aircraft DG and if equipped, navigational aids, including VOR/LOC and GPS, are required to provide the desired autopilot lateral-navigation features. For this system, a WAAS-capable GPS is a requirement in order to provide lateral positioning that is sufficiently accurate for autoland capability.
- **User Inputs**—In addition to the typical autopilot and envelope protection controls described previously, an autoland function would require pilot selection of a desired airfield (nearest by default) and an activation of the autoland feature. The specific runway for landing could be chosen from a menu, or by default, the most favorable runway, given the winds as estimated by the system, would be chosen.

The autoland feature would provide the most robust possible protection against a very unlikely scenario that is a real concern for single-pilot operators: the possibility of pilot incapacitation with nonpilot passengers aboard. The procedure for the passengers to follow in case of pilot incapacitation would become as simple as “push this button.”

- **Algorithms**—In addition to the full-featured autopilot, caution and warning, and envelope protection algorithms already incorporated into System V, there would be several important advanced features required for this system. These would include throttle control logic (particularly helpful in recovering from overspeed conditions and essential for autoland) and the autoland algorithms themselves. Throttle actuation authority would provide the ability to have an additional vertical autopilot mode in which both airspeed and climb rate are selected independently (within the performance capabilities of the aircraft). Autoland algorithms could be a relatively straightforward, trajectory-following feedback control, where the desired aircraft state history of a normal landing under constraints would constitute the setpoint for multistate control. The constraints would include a sideways drift rate close to zero (necessitating deliberate uncoordinated flight in a crosswind landing) and a prescribed vertical rate at touchdown. A “go-around” capability would be important to include in case a last-minute decision was made to abort the landing (for example, obstacles on the runway).

Despite the perceived sophistication and difficulty of an autoland capability, the actual implementation of such a function is not that great a step to take, once full state

information is available and full actuation authority is provided. For retractable gear airplanes, the need to put the gear down could be accommodated either by appropriate annunciations to the crew or by an interface to the gear actuation system itself. For the class of aircraft considered, flaps for landing are an optional item in most cases, except for the shortest runways.

- Displays/Outputs—Displays and audio annunciations would be similar in most respects to System V, with additions to support autoland, and the new autopilot modes made possible by autothrottle capability. As in previously described systems, audio and visual alerts are provided, as are alerts whenever the system intervenes in any of its envelope protection control functions. Mode annunciations for autopilot modes are, of course, provided. In particular, audio and visual annunciations to keep the aircraft crew and occupants fully informed during autoland would be of critical importance.
- Actuation—Full three-axis aileron, elevator, and rudder control are provided, both for autopilot functions and for envelope protection functions. Servo control of throttle is a necessary addition for this system. Servo control of landing gear is an optional addition. Servo control of propeller speed and flaps are not essential; advisories can be furnished to the crew and occupants if deemed appropriate.

3. BASIC ADVISORY SYSTEM DEVELOPMENT.

As part of the first-year effort, the concept of the Basic Advisory System was refined further, and a basic prototype was developed and test flown.

3.1 CONCEPTUAL ADVISORY SYSTEM PRODUCT.

A complete advisory system product could warn against several dangerous conditions, including stall/spin, overspeed, and over-g. Additional airframe configuration warnings could also be issued with the addition of suitable external sensor inputs.

3.1.1 Incipient Spin Warnings.

An aircraft that is uncoordinated in flight is more likely to spin if the critical AOA is exceeded. Accelerometer measurements can be used in the Basic Advisory System to indicate danger of a spin due to an uncoordinated condition in combination with flight near-critical AOA.

3.1.2 Overspeed Warnings.

An overspeed warning is issued if airspeed approaches the aircraft's never-exceed speed. An additional advisory to slow to maneuvering speed can also be issued in the event that high levels of turbulence are detected while the aircraft is operating above this speed.

3.1.3 Over-g Warnings.

Airframe g loading can be measured directly with the three-axis accelerometer planned for the Basic Advisory System. In the event that accelerations are detected that approach the design limits of the aircraft, appropriate cautions and warnings will be issued.

3.1.4 Additional Warnings.

Leveraging the capability of the unit further for retractable-gear aircraft, a gear-up warning can also be issued at low airspeed if the necessary connections to landing gear status switches are included during installation.

3.1.5 Display and Aural Warning Concepts.

No visual display is needed to satisfy the requirements of 14 CFR 23 for stall warning. Therefore, ideally, the instrument would be certified to work without the display. However, a display would add value to the unit.

Current convention with respect to lift reserve and AOA indicators is to display low AOA conditions with green and progress through yellow and red as higher-AOA conditions are encountered. The proposed concept maintains that convention but places several other indications on the display as well.

In figure 7, the display is laid out within the frame of a standard 2 1/4" instrument face. In cases of limited panel space, a smaller display might be warranted. In keeping with convention, a graphical representation of AOA is shown as a series of bars that light and change color as AOA is increased. The same display method is also used for g loading. In addition to the vertical color bars, numerical values are also given. The numerical AOA display allows the pilot to use the information for purposes other than stall warning. For instance, best climb and best glide correspond to particular AOA values that do not depend on aircraft weight, unlike the corresponding airspeeds. The center of the display includes a location for text-based warning messages. The output from the lateral accelerometer is displayed in a manner similar to the inclinometer from the original turn coordinators.

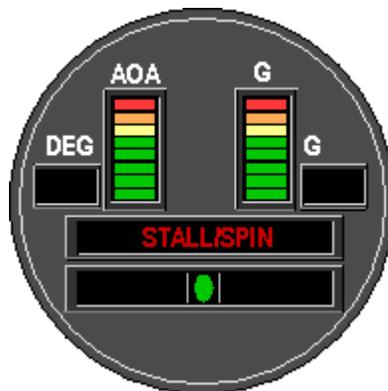


Figure 7. Initial Concept for Basic Advisory System Display

Figure 8 shows the instrument at low AOAs. No warnings are displayed and the AOA bars are in a low position. If the aircraft is subjected to uncoordinated flight, the instrument responds with a deflection on the display. Large deflections are indicated by a color change on the indicator. Note that large deflections of the “ball,” while displayed as red, could be deliberate on the part of the pilot (as in the case of a normal forward slip during landing approach), and therefore, no aural warning would be annunciated.

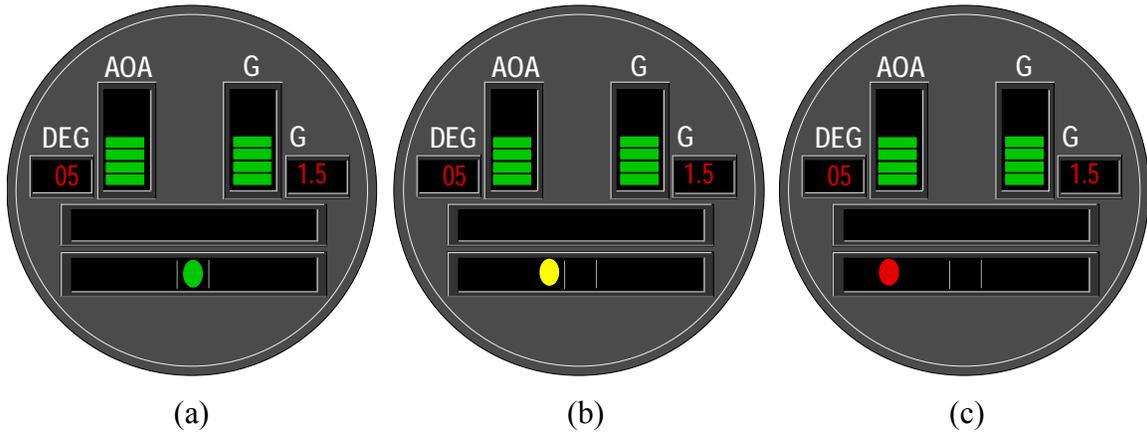


Figure 8. Display (a) Coordinated, (b) Uncoordinated, and (c) Severely Uncoordinated

Figure 9 shows the instrument display at a large AOA. In this condition, the instrument will indicate a stall warning if the aircraft is coordinated. If an uncoordinated condition exists, a stall spin warning will be displayed. Aural warnings accompany the visual warnings in these cases.



Figure 9. Display (a) at High AOA and (b) in a Spin Scenario

Figure 10 shows the instrument display with the aircraft in a coordinated but very high-g maneuver. In this condition, the high-g display would be accompanied by an aural warning as well.

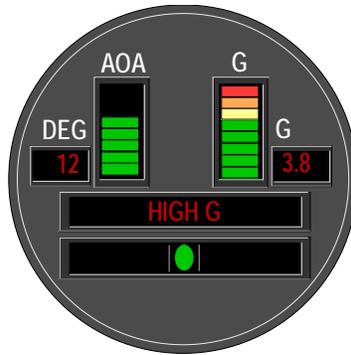


Figure 10. Display in a Very High-g Maneuver

3.1.5.1 Limited Space Solutions.

In some cases, panel space is not available for regular-sized instruments. In these cases, smaller displays could be developed that can be mounted in the panel or elsewhere, in some cases. An example of such a display is the AOA Sport Display shown in figure 11. This display could be mounted on an interior plastic panel, such as a doorpost panel on a C-172 or C-182 class aircraft.



Figure 11. Limited Space Display by AOA Sport Instruments

3.1.5.2 Aural Warning Concepts.

Two levels of aural advisory are proposed. The first level advises the pilot of the dangerous situation, if the dangerous situation persists or gets worse, the next advisory level will advise the proper control action. There are five advisories for stall and stall/spin:

- CAUTION STALL
- CAUTION STALL/SPIN
- PUSH FORWARD
- PUSH FORWARD/LEFT RUDDER
- PUSH FORWARD/RIGHT RUDDER

For overspeed and over-g warnings, a similar philosophy would be followed. Aural warnings should have a warning tone in addition to the vocal advisories. The vocal advisories can be stored as *.wav files and played as needed.

3.1.5.3 Caution and Warning Logic.

Figure 12 shows proposed logic for stall and stall-spin warnings. The logic features two different values of AOA, α_1 and α_2 . The first value, α_1 , triggers an initial warning that the critical AOA is approaching. At this level, advisories are issued to warn of the potential situation. The second level, α_2 , represents the onset of stall and the more urgent warnings are issued.

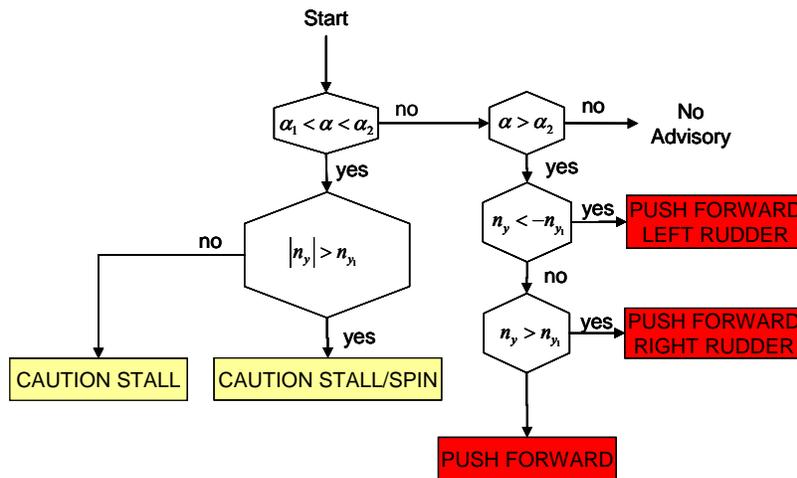


Figure 12. Example Logic for an Advisory System

Figure 13 shows logic that could be implemented for overspeed and over-g warnings.

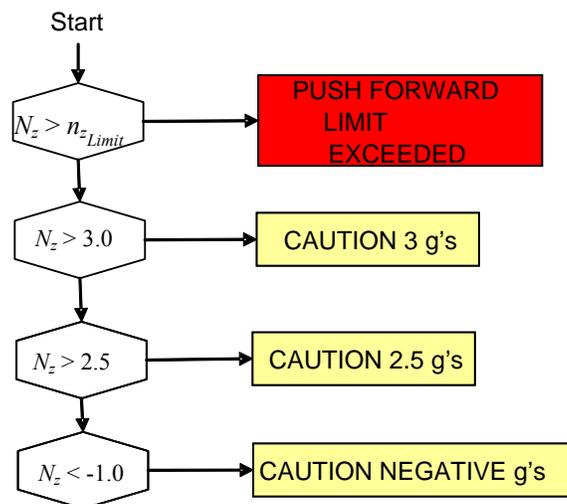


Figure 13. Potential Logic for g-Loading Advisories

For g loads above 2 g's, the advisory system issues alerts. Since high-g loads under the limit load are not necessarily dangerous, a simple caution advisory is issued. Once the limit load is exceeded, a more urgent warning is issued. The warning indicates the corrective action first (e.g., push forward) and then states the dangerous situation.

3.1.6 Determining AOA.

For the purpose of advisory systems and envelope protection, aircraft AOA can either be directly measured or estimated using airspeed and known physical principles.

3.1.6.1 Direct AOA Measurement.

AOA can be directly measured using a pitot tube with special ports, two or more pressure ports on the bottom and top surfaces of a wing, or from a weather cock or vane-type detector. Generally, pitot tube probes are more durable than vanes and easier to mount and calibrate than wing-mounted pressure ports. A representative two-port pitot tube is shown in figure 14.

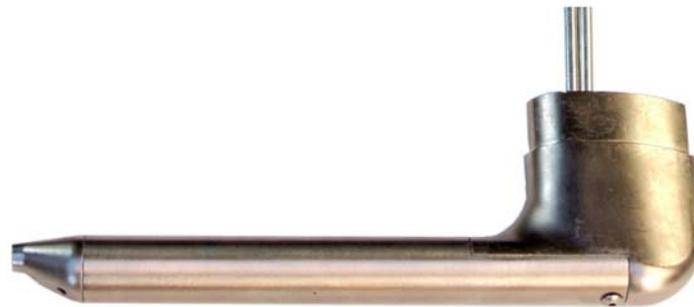


Figure 14. Pitot Tube With a Second Canted Port to Enable AOA Measurement

3.1.6.2 Alternatives to Direct AOA Measurement.

AOA of the aircraft can be estimated using measured acceleration and airspeed. In equation 1, measured acceleration is equal to the lift being produced by the airframe, divided by aircraft mass

$$a = L / m \quad (1)$$

where

a = acceleration

L = lift

M = mass

In equation 2, lift is equal to dynamic pressure (a measured quantity) times a reference area, times the coefficient of lift

$$L = \frac{1}{2} \rho_{SL} V_{IAS}^2 S C_L \quad (2)$$

where

ρ_{SL} = air density at sea level
 V_{IAS} = indicated airspeed
 S = reference area
 C_L = coefficient of lift

Therefore, the coefficient of lift can be calculated from accelerometer measurements and the measured airspeed of the aircraft as

$$C_L = \frac{a / m}{\frac{1}{2} \rho_{SL} V_{IAS}^2 S} \quad (3)$$

This relationship is valid whether the aircraft is in straight-and-level flight or is maneuvering. Therefore, it is generally useful for detecting any situation in which the coefficient of lift (and necessarily the AOA) is approaching critical values, as in the cases of a stall in straight-and-level flight, or an accelerated stall during maneuvering.

Once the lift coefficient is determined, AOA can be determined. However, the relationship between lift coefficient and AOA is aircraft-type specific, and therefore, a parameter associated with the particular aircraft type would have to be included in the calculations for this approach to be viable. Furthermore, the maximum coefficient of lift is also dependent upon whether flaps are deployed or not, and this may create additional difficulties in using this estimation approach.

However, the major potential inaccuracy in estimating AOA using this method is uncertainty in the weight of the aircraft. As an example, a well-equipped Beechcraft Bonanza has an empty weight of 2650 lb and a maximum gross takeoff weight of 3650 lb. With only a light-weight adult pilot (150 lb) and minimum fuel (15 gal at 6 lb/gal, or 90 lb) aboard, the actual aircraft weight might be as little as 2890 lb. The practical operational variation in aircraft weight is, therefore, about 20% of the maximum gross takeoff weight. If the actual weight is assumed to be the maximum, the calculated coefficient of lift would be in error by 20% and the estimated stall speed in straight-and-level flight would be too fast by 10%. Without some means of determining actual aircraft weight, this magnitude of error is probably too great to be tolerable in practice for most envelope protection applications.

While innovative solutions to these complications are not yet out of the question, these considerations move the researchers toward inclusion of an actual AOA measuring device for envelope protection applications, wherever practicable.

3.2 ADVISORY SYSTEM PROTOTYPE.

A basic advisory system prototype was constructed and flight tested during the first year of this research, with the limited goal of demonstrating a stall/spin detection capability. g-load and overspeed warnings were not implemented in this initial prototype, although the sensors necessary to implement these warnings were included.

The prototype system uses pitot/static inputs to determine indicated airspeed, with a second canted pitot port to enable AOA sensing. It also has a three-axis accelerometer and a two-axis tilt sensor. The accelerometers are used to measure airframe acceleration and the tilt sensors are used to control the accelerometer bias drift. Using this set of sensors along with a central processing unit (CPU) and display (see figures 15 and 16) enables the detection of several dangerous scenarios. A GPS receiver, while unnecessary for the functions being examined, was included in the initial prototype to aid in flight data analysis.

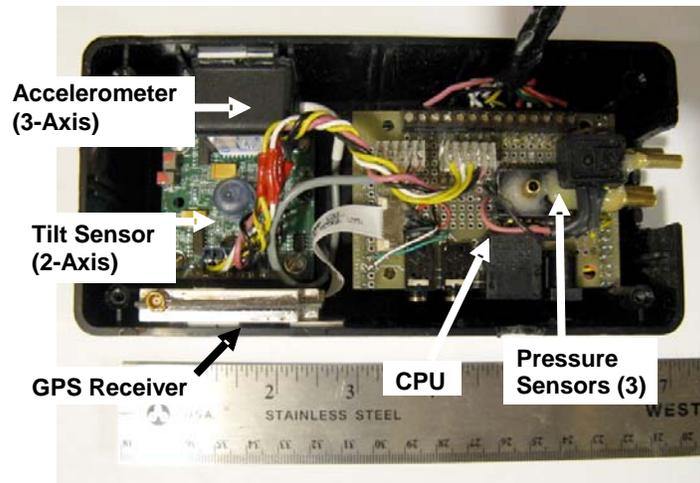


Figure 15. Stall Spin Warning Module Prototype Electronics

An initial prototype display used for flight testing (figure 16) consisted of a simple arrangement of light-emitting diodes (LED). The low AOA conditions are indicated with green and progress through yellow and red, as higher AOA conditions are encountered. The concept places additional LEDs laterally at the top of the display to indicate an uncoordinated situation. As with a turn coordinator, a lateral indication indicates needed rudder application. When the aircraft is on the verge of stall, all the LEDs flash.



Figure 16. Prototype Display for Stall Spin Warning

From data gathered in the initial flight tests, measurements from a dual-port pitot probe were adequate to determine aircraft AOA and provide a repeatable warning of the development of a near-stall condition. This was true for the full range of flap settings available on the particular aircraft in use, a Cessna 182. After calibration of the AOA sensing capability of the prototype, the unit was tested in flight and was effective in providing warning of incipient stall and incipient stall spin conditions. The warning logic and display concepts were adequate to provide timely and unambiguous indications to the pilot of the need for corrective action to prevent a full stall or the development of an incipient stall spin into a departure from controlled flight.

4. AUTOPILOT AND ENVELOPE PROTECTION USING TRADITIONAL ACTUATION METHODS.

4.1 BACKGROUND.

This effort was originally intended to demonstrate how envelope protection and other sophisticated autopilot functionality could be embedded in autopilots of traditional design. Traditional design in this context refers to a sensor package of varying sophistication, coupled to a digital autopilot, which in turn, drives traditional servo-actuators. Using conventional actuation, the envelope protection can only monitor operations until a particular dangerous situation is detected and then engage the rigid servo, thus actively taking control from the pilot. The autoflight system remains in control of the aircraft until the pilot disengages it or until it disengages itself when a certain safe state is reached. Because of the discontinuity between the engaged system and the disengaged system, it is important that visual and audible warnings be provided so the pilot is aware of the impending activation of the envelope protection system.

The development of the Force Gradient Control concept (see section 5) has changed the focus away from the use of traditional actuation in an effort to provide a continuous envelope protection solution. However, since traditional actuators are prevalent in the GA community and because some solutions might involve the partial use of previously installed equipment, the consideration of envelope protection within the scope of traditional actuation is still relevant.

4.2 ENVELOPE PROTECTION FUNCTIONALITY.

Figure 17 shows a hypothetical display for an envelope (EV) protection system. In this system, the pitch (PCH), bank (BNK), and AOA of the aircraft are monitored. To provide protection, the system has to be armed, which should be an automated startup function. The EV button, shown in figure 17, indicates that the system is on and armed when illuminated. The EV button also serves as a means of disabling the device if necessary, or if desired for certain types of special-purpose flight operations (for example, flight training involving steep turns or full stall and recovery maneuvers).

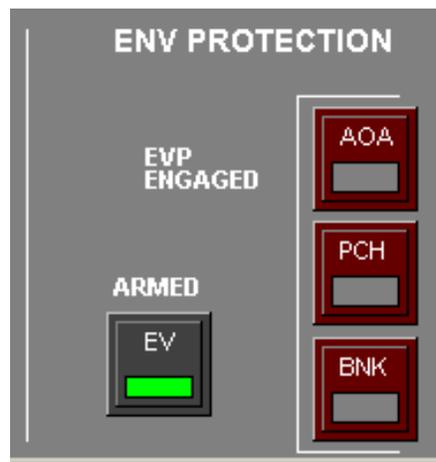


Figure 17. Hypothetical Display for Envelope Protection System

The status and control of each individual envelope protection feature is accomplished with the three magenta buttons labeled AOA, PCH, and BNK, respectively. The envelope protection functions are engaged when their respective parameters exceed predefined limits. When one or more systems are engaged, the corresponding buttons (AOA, PCH, and/or BNK) are illuminated with an amber light. Once the system is engaged, the autopilot assumes control of the aircraft and provides the corrective input. Control is returned to the pilot when the envelope protection system determines that the corrective action is complete and the protection function is disengaged. The pilot also has the option of manually disengaging the function by depressing the respective button.

In addition to the visual display of envelope protection activation, an audio annunciation of the feature's activation would also be presented. This would not be a nonspecific tone or bell, but rather a verbal message such as the phrases "Angle of Attack Protection Engaged" and "Angle of Attack Protection Disengaged."

4.2.1 Angle of Attack Protection.

AOA envelope protection would function in a similar manner to a stick pusher system. At some AOA close to, but not exceeding, the critical AOA, the system is engaged and pitches the aircraft down to achieve a suitably reduced AOA, at which time the system disengages. Figure 18 shows the envelope protection logic. The envelope protection system differs from a conventional stick pusher in that it is not necessary to simulate the nose-down pitch motion of a conventional stall, which would require a large spread between the engage and disengage values for AOA. Rather, the spread between the engage and disengage AOA values ($\alpha_{engage} - \alpha_{disengage}$) is kept small to reduce the pitch correction to the minimum amount required to provide a safe stall margin.

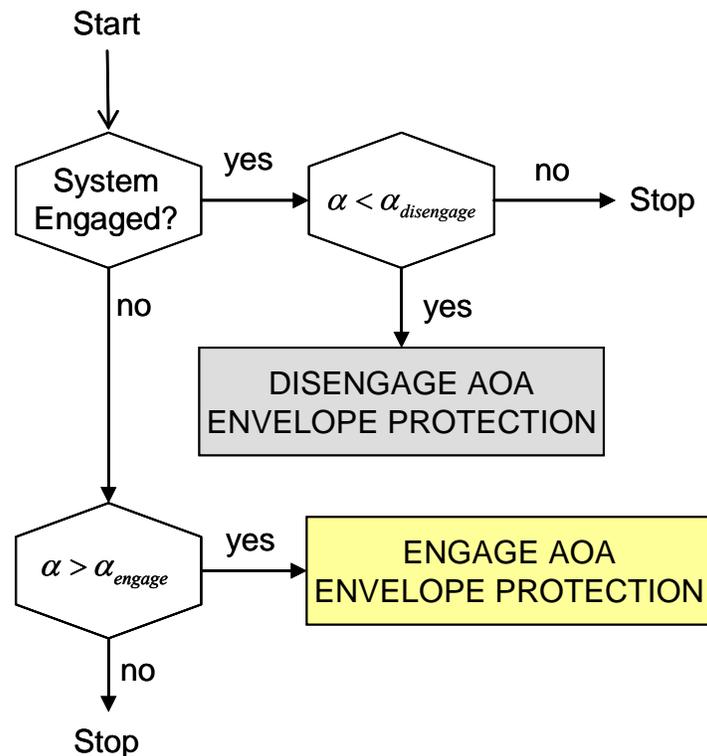


Figure 18. An AOA Envelope Protection Logic

4.2.2 Bank Angle Envelope Protection.

Bank angle envelope protection is activated when the bank angle of the aircraft exceeds a specified value. The bank angle at which envelope protection should be activated is still a matter for further analysis, but nominally, 45 degrees is considered a reasonable value. The logic for bank angle envelope protection is shown in figure 19. When the bank angle, ϕ , exceeds the activation angle, ϕ_{engage} , the system activates a wing leveler algorithm. Once the wing leveler is activated logic is engaged to determine when it should be disengaged.

One possible algorithmic approach is to activate the leveler long enough to roll the aircraft back within the safe bank angle bounds. Another is to engage the leveler long enough to roll the

aircraft back to a wings-level condition. At this point, it is not clear which approach would be most desirable. In the event that a wings-level condition is chosen for the disengagement criterion, prior to disengaging the wing leveler, the algorithm must detect that the aircraft is in a steady, wings-level condition. To ensure that the bank angle is steady, the roll rate, p , must be measured in addition to the bank angle. Assuming both are small, the wing leveler is disengaged.

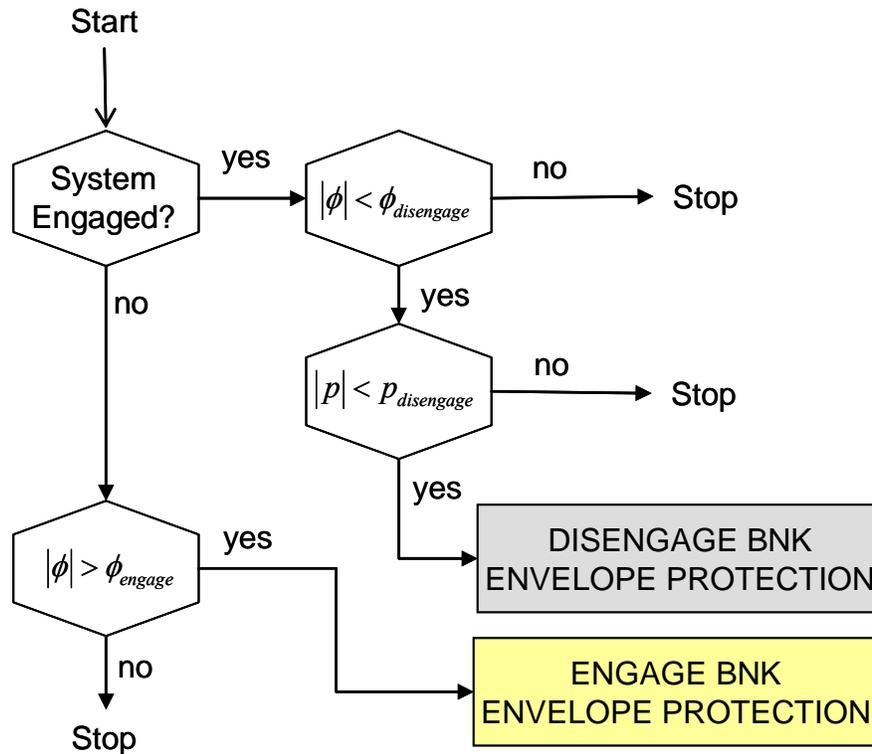


Figure 19. Bank Angle Envelope Protection Logic

4.2.3 Pitch Angle Envelope Protection.

Pitch angle envelope protection is activated when the pitch angle of the aircraft exceeds a specified value. The angle at which it should be activated is still a matter for further analysis, but nominally, a pitch angle of $\pm 20^\circ$ is considered reasonable. The logic for pitch angle envelope protection is shown in figure 20. Unlike AOA, it is insufficient to just reduce the pitch angle using elevator deflection, because it is likely that a large pitch angle, if corrected abruptly, could cause undue oscillations. In this sense, the pitch envelope protection system most resembles the bank angle system. When the pitch angle, θ , exceeds the activation angle, θ_{engage} , a pitch control law is activated. The pitch control law returns the aircraft to a level flight condition. To disengage the pitch control, the algorithm must detect when the aircraft is in a steady, nose-level condition. To ensure that the pitch angle is steady, the pitch angle rate, $\dot{\theta}$, must be measured in addition to the pitch angle. Assuming both are small, the pitch controller is disengaged. It is important to use $\dot{\theta}$, rather than the body pitch rate, q , since q is nonzero during turns.

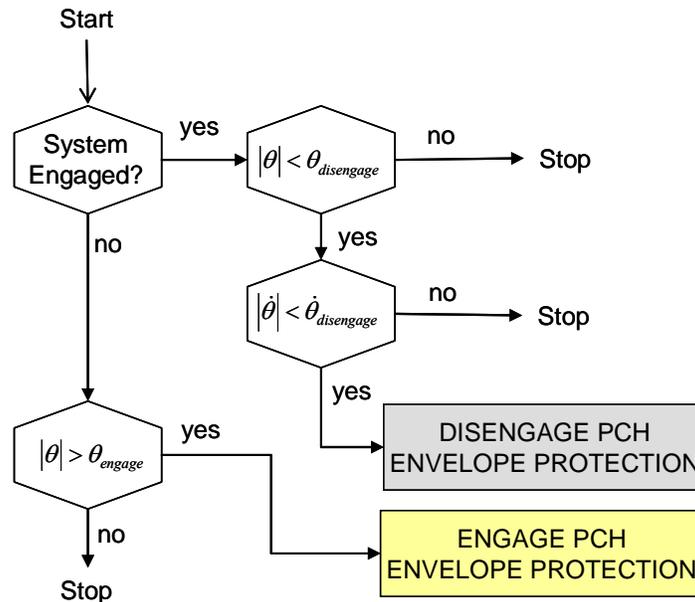


Figure 20. Pitch Angle Envelope Protection Logic

5. AUTOPILOT AND ENVELOPE PROTECTION USING FORCE GRADIENT CONTROL.

Force Gradient Control is a new concept in control surface actuation which enables simultaneous pilot/servo actuation of a control surface. This section introduces Force Gradient Control and presents one potential implementation in an autoflight system.

5.1 BACKGROUND.

In comparison to transport and military aircraft, GA aircraft control systems are technologically simple yet effective. These control systems are reversible (i.e., cable-actuated and directly connected to the flight controls). With GA autopilots, the autopilot actuator and the pilot act on the same cable. There is no summing of signals or intrinsic mechanism for implementing pilot-in-the-loop stability augmentation. However, due to the reliability and economy of cable-actuated systems, it is also difficult to justify replacing them with fly-by-wire systems. This is especially true of retrofit systems.

The reversible control system presents problems for implementing envelope protection. How can some measure of stability augmentation be provided to an aircraft when the activated servo precludes any pilot input? Using conventional actuation, the envelope protection can only monitor operations until a particular dangerous situation is detected and then engage the rigid servo, thus actively taking control from the pilot. The autoflight system remains in control of the aircraft until the pilot disengages it, or until it disengages itself when a certain safe state is reached. Of course with proper human factors design, this transition can be smoothed through the use of visual and audible warnings so the pilot is aware of his impending loss-of-control, but it does not eliminate completely the inherent undesirability of such an arrangement.

For aircraft using nonreversible controls, such as fly-by-wire systems, the limitation of the direct flight control-to-control surface connection does not exist. The task of control augmentation while the pilot is manually flying the aircraft is straightforward. As shown in the fly-by-wire system example in figure 21, the pilot commands are inputs to the flight control computers along with measured state information. The flight control computer then provides the actuation signals to move the surfaces. Artificial force feedback mechanisms may even be employed to give the pilot the appropriate stick force gradients. However, such a system is extremely complex and expensive for a light GA aircraft. While not inconceivable, it is highly unlikely that such a system could be retrofitted into an existing aircraft at an appropriate price point.

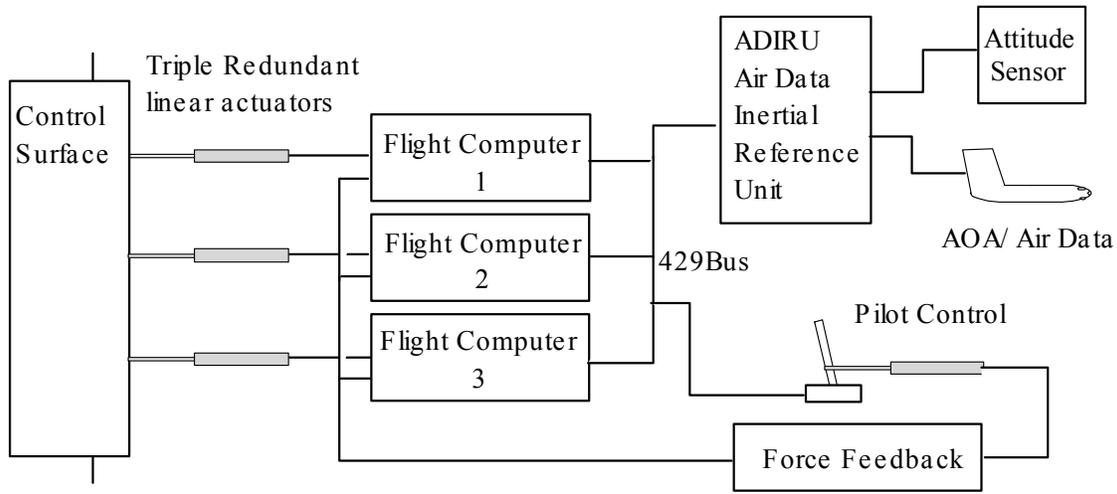


Figure 21. High-Level Component Diagram of Fly-by-Wire Flight Control Systems

An inherent design limitation exists, and it is unclear how to effectively provide stability augmentation to an aircraft with reversible controls and servos that are rigid so that the pilot cannot move the activated servo.

5.2 CONVENTIONAL GA ACTUATORS.

The conventional GA autopilot actuator is best described as a heavily geared torque motor that is designed to move and hold an aircraft's control surface at a particular location, as shown in figure 22.



Figure 22. Classical GA Servo Actuator

The conventional actuator has five main components, as shown in figure 23. These components are a DC torque motor, a high-reduction gearbox, a clutch, a shear pin, and a spindle.

A DC torque motor is an induction motor that is capable of operating indefinitely while stalled (prevented from turning) without incurring damage. In this mode of operation, the motor applies a steady torque to the load. The motor used in the application is designed to run on DC power from the aircraft bus. The motor engages a high-reduction gearbox that creates a high torque, but at a very low rpm.

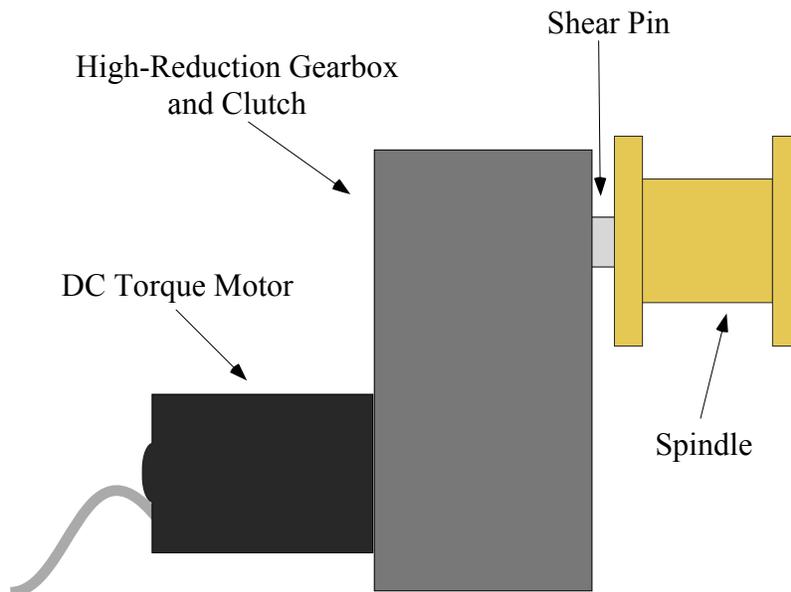


Figure 23. Five Main Components of a GA Servo Actuator

The clutch engages when the servo is activated and locks the spindle to the gearbox. When the clutch is disengaged, the spindle can spin freely. The clutch may or may not have the ability to slip when the applied torque exceeds a specified value, allowing the pilot to manually override the servo.

- The spindle is used to engage the servo to the actuating control cable.
- The shear pin located between the clutch and the spindle is designed to break at a specified torque to provide another means for the pilot to override the servo; in this event, the system is disabled until another shear pin is put in place.

The servo is incorporated into the control system using an additional servo cable, as shown in figure 24. The servo is mounted near the aircraft control cable but in a manner that will not interfere with the cable's operation. Then an additional servo cable is wrapped several times around the servo spindle and attached using clamps to the aircraft control cable. This manner of installation ensures that the original control system is left intact.

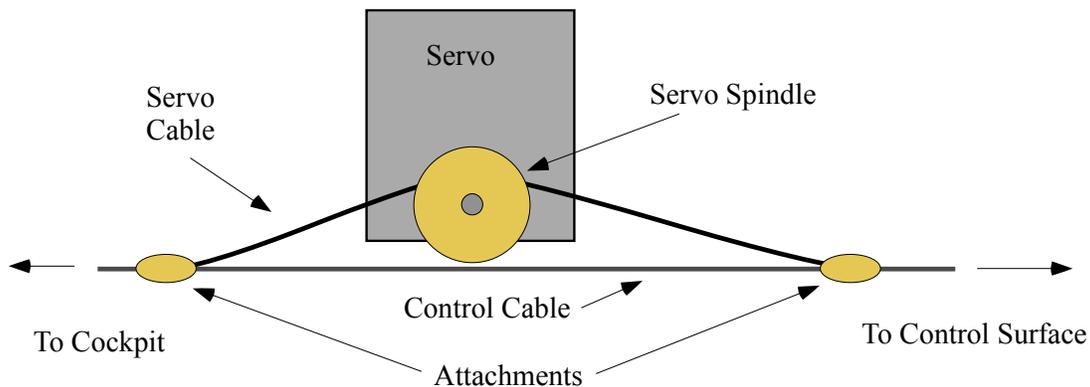


Figure 24. Incorporation of a Servo in a GA Flight Control System

In legacy autopilot systems for light aircraft, the servo is usually an open-loop device, where the control system provides a signal voltage used to drive the servo motor. Neither the position nor the speed of the spindle are measured and fed back to the control system. The signal voltage is sent to a control amplifier, as shown in figure 25, which in turn, outputs an appropriate voltage to drive the servo motor. A typical servo motor runs on ± 14 volts, where the polarity of the voltage controls direction.

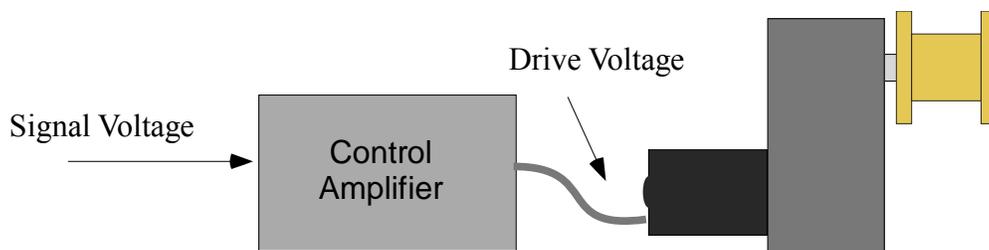


Figure 25. Nature of Operation of Servo

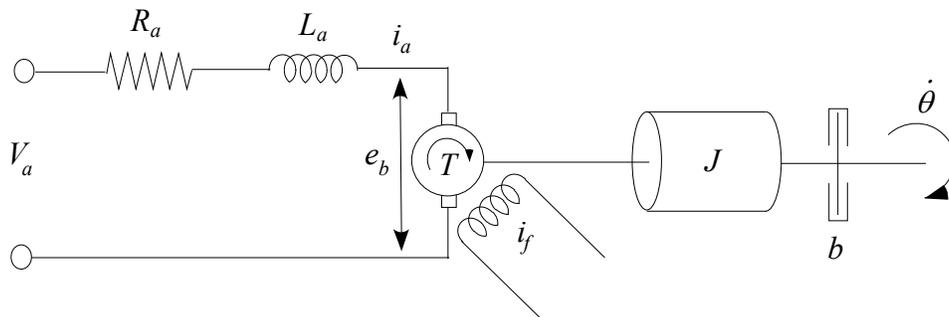
The servo provides the ability to position a control surface and enough resistance to motion through the gearing and the motor torque to maintain the surface position against the applied loads on the surface. However, the force applied to the control cables is not controllable, per se, and the servo gear train is not readily back drivable. Because of the nature of these servos, the pilot and the autopilot cannot exert control of the aircraft at the same time. Either the pilot or the autopilot can manipulate the flight control surfaces, but both cannot simultaneously exert an influence on them.

5.3 FORCE GRADIENT SERVO.

The force gradient servo is a new servo concept that was born out of the limitation of the classical servo design. It was suggested that if a servo could be built that would provide a constant torque regardless of its angular position and also be freely back drivable by an outside source, it could provide a means where an autoflight system could be continuously engaged and not interfere with manual flight operations. Such a servo would provide the link between fly-by-wire stability augmentation and an aircraft with reversible controls.

5.3.1 Motor Theory.

Consider the operation of a classical torque motor, as shown in figure 26. In this particular motor, the armature and the field are controlled from different sources and the field current is held constant. The armature voltage is varied to control the motor.



R_a = Armature resistance (ohm)	e_b = Back electro-motive force (EMF) voltage
L_a = Armature inductance (henry)	θ = Angular position of the motor (deg)
i_a = Armature current (amp)	J = Moment of inertia of armature and shaft (slug·ft ²)
i_f = Field current (amp)	b = viscous friction coefficient, $(\frac{ft \cdot lb}{deg \cdot sec})$
V_a = Armature voltage	T = Motor torque, ft·lb

Figure 26. Classical Torque Motor

The torque produced by the motor is proportional to the product of the armature and field currents. Since the field current is constant, the torque can be directly related to the armature current through a constant, K [7].

$$T = Ki_a \quad (4)$$

When the armature is rotating, back EMF voltage proportional to the speed of the armature's rotation is produced. This voltage is referred to as e_b and is related to motor speed through a constant, K_b .

$$e_b = K_b \frac{d\theta}{dt} \quad (5)$$

The current through the motor is determined by equations 6 and 7. When the motor spins, the back EMF impacts the current flow.

$$-V_a + R_a i_a + L_a \frac{di_a}{dt} + e_b = 0 \quad (6)$$

$$-V_a + R_a i_a + L_a \frac{di_a}{dt} + K_b \frac{d\theta}{dt} = 0 \quad (7)$$

For a motor that is not under load, the inertia and friction of the motor can be represented by equation 8. The expression relates the torque to the rotor speed, which ultimately impacts the current flow.

$$J \frac{d^2\theta}{dt^2} + b \frac{d\theta}{dt} = T = Ki_a \quad (8)$$

Using these expressions, it is possible to construct a transfer function relating the position of the motor shaft to the applied voltage, which is classically represented by equation 11.

$$-V_a(s) + R_a I_a(s) + L_a s I_a(s) + K_b s \Theta(s) = 0 \quad (9)$$

$$Js^2 \Theta(s) + bs \Theta(s) = KI_a(s) \quad (10)$$

$$\frac{\Theta(s)}{V_a(s)} = \frac{K}{s(JL_a s^2 + (JR_a + bL_a)s + (KK_b + bR_a))} \quad (11)$$

However, the objective here is to control torque directly rather than speed. Therefore, a transfer function relating current to position is first obtained (equation 12).

$$\Theta(s) = \frac{K}{Js^2 + bs} I_a(s) \quad (12)$$

Substituting equation 11 into equation 12 yields the following expression for the transfer function from applied voltage to motor current.

$$\frac{I_a(s)}{V_a(s)} = \frac{Js + b}{JL_a s^2 + (JR_a + bL_a)s + (KK_b + bR_a)} \quad (13)$$

Motor torque is simply motor current times the constant K (equation 4) [8]. Using this physical model of the motor, a simple control loop can be designed that uses current feedback to a regulator to control the torque of the motor independent of its speed.

The motor dynamics are described, in block diagram form, in figure 27. The motor is controlled by the input voltage. The motor current, torque, and shaft position are the outputs. In addition, a load torque is usually applied to the motor shaft as well.

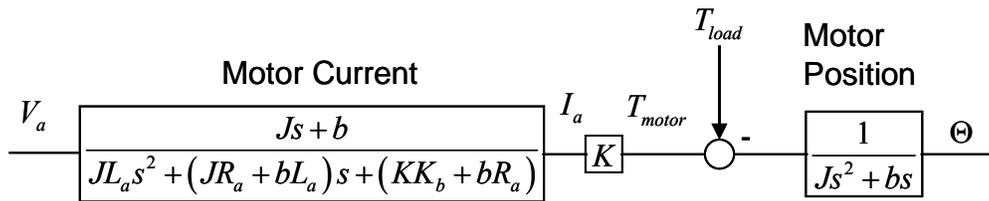


Figure 27. Motor Block Diagram

To control the motor, both the motor current and the motor shaft position are used for feedback, as shown in figure 28. The current of the motor is measured and fed back to the motor controller. The motor controller regulates the motor voltage to maintain a desired current, and therefore, a desired torque. The total applied torque to the shaft is a function of the motor torque and the torque of the load, which in this case, comes from a deflected control surface and/or pilot input. The sum of the torques then causes the shaft to rotate.

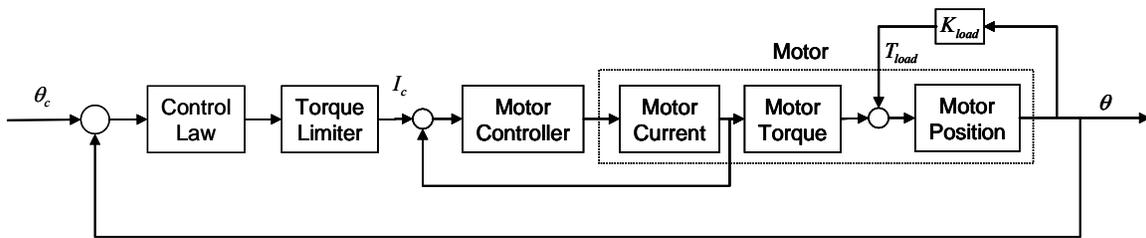


Figure 28. Motor Block Diagram With Control

The shaft position is measured and fed back to an outer-loop control law that attempts to drive the motor to a particular angular position. The control law determines a commanded torque value as a command input for the motor controller; however, between the control law and the motor controller is a torque limiter, which effectively limits the allowable commanded current to the motor controller. In effect, the control system attempts to drive the motor shaft to a desired position but will not exceed a particular torque value in its attempt to do so.

5.3.1.1 Practical Considerations.

There are several practical considerations to the development of the force gradient servo. For the servo to be easily back-driven, it cannot have the same type of gear box that a conventional servo uses; such gearboxes were not designed to be back-drivable, which is a necessary design requirement for the servos to be used in force gradient control.

Small, high-performance DC motors are available today that were not in existence at the time that most autopilots in GA aircraft were designed. In addition, mechanical-engineering technology has advanced, particularly in gear-train design, and the available characteristics for gearing or belt-driven systems today far exceed what was in existence several decades ago.

Important factors to consider in choosing a motor and drive design are:

- Required torque
- Available motor torque versus motor size and weight
- Acceptable levels of gear- or belt-train backlash, stiction, and inertia
- Available and required power
- Ease of providing servo-position pickoff

5.3.1.2 Conceptual Design.

Figure 29 shows one basic conceptual design for the servo actuator assembly. It is similar to the conventional servo in that it maintains the same basic shape and consists of a motor, reduction unit, shear pin, and spindle. However, in this hypothetical unit, a belt reduction unit (figure 30) is used rather than a gearbox. Using a belt reduction unit, the servo motor can be back-driven with relative ease. Additionally, the servo has a motor controller that contains a current feedback regulator to regulate motor torque.

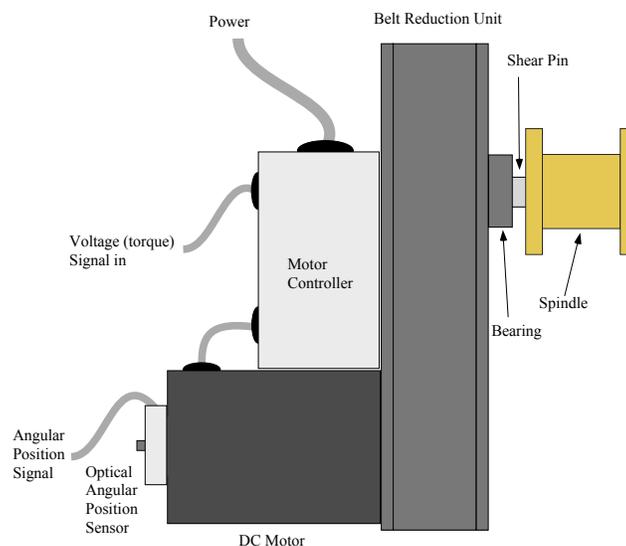
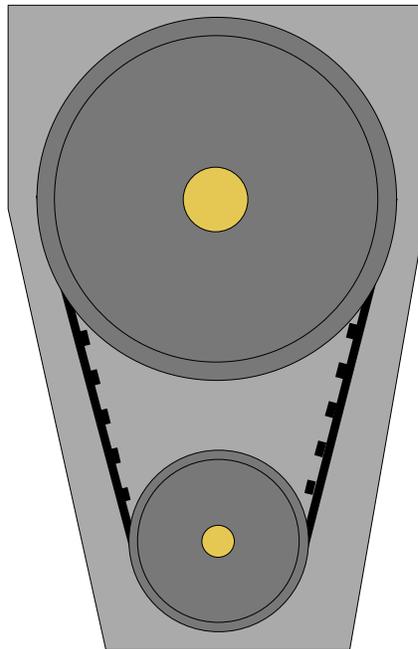


Figure 29. Force Gradient Servo Conceptual Design



The actual belt reduction unit may employ multiple belts and wheels to provide adequate mechanical advantages to the motor. Belts may yield lower stiction and backlash and higher reliability than advanced gear systems; however, this is still a subject for further research

Figure 30. Example Belt Reduction Unit for the Force Gradient Control Servo

The input control signal is a voltage proportional to the desired torque. Additionally, an angular position sensor, most likely an optical sensor, is mounted on the motor for measuring servo displacement. A means for verifying the relationship between the motor angular position sensor output and control surface deflection at system startup is provided (not shown in the figure; one example might be a small magnet and Hall-effect sensor within the cable system.)

This servo does not require a mechanical clutch because it is designed to be back-drivable and creates minimal drag on the system when not powered; however, a shear pin is still included in the design for safety.

Most of the components required for this servo design concept are used in industrial applications and are readily available. Small and powerful DC torque motors using rare-earth magnets of various sizes and capabilities are available from a large number of suppliers. Constant current controllers are also widely used and come in prepackaged units that can be tailored to a particular application. Optical sensors are commonly used to determine motor position in such applications, and belts and pulleys are readily available. The housing and spindle are the only special-purpose parts that would likely not be available as off-the-shelf components and would require fabrication.

5.4 FORCE GRADIENT METHODS APPLIED TO LATERAL CONTROL.

In the discussions that follow, it is assumed that the aircraft under discussion is equipped with a digital AHRS and air data unit. This is not an essential requirement for some subsets of envelope protection capability that could be implemented using force gradient control, but is a useful starting point for conceptual purposes.

The basic functionality of a conventional lateral autopilot for light aircraft is to maintain a wings-level condition (i.e., control bank angle). More sophisticated systems will enable to pilot to command a heading or track a course, but these features are given effect by specifying a series of bank angle commands to the control law inner loop.

In the force gradient control concept, the flight control behaves as the conventional autopilot when explicit autopilot functionality is activated, but remains engaged even when explicit autopilot functionality is deactivated. In this mode, the flight control provides two additional functions: (1) mild stability augmentation and (2) envelope protection. In this section, basic autopilot functionality is explored and then expanded to include stability augmentation and envelope protection.

5.4.1 Lateral Conventional Autopilot Functionality.

To achieve conventional autopilot functionality, a simple lateral control law can be implemented. The natural integral relationship between aileron deflection, δ_a , and bank angle, ϕ , guarantees a zero steady-state error without the use of integral control. Therefore, a single proportional gain control law with gain, k_ϕ , can maintain level flight. If some additional roll damping is required, the roll rate, p , can be fed back, as well using another proportional gain, k_p . The block diagram for this control law is shown in figure 31.

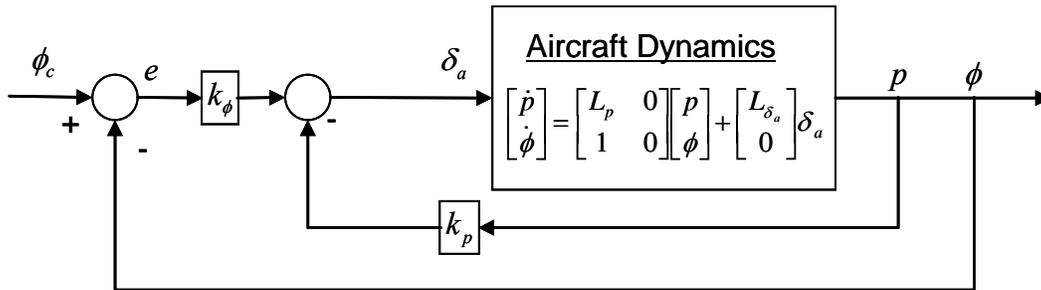


Figure 31. Basic Control Law for a Wing Leveler

The closed loop ($\frac{\phi}{\phi_{des}}$) transfer function is shown in equation 14. The DC gain of the transfer function is unity.

$$\frac{\phi}{\phi_{des}} = \frac{L_{\delta_a} k_\phi}{s^2 + (L_{\delta_a} k_p - L_p)s + L_{\delta_a} k_\phi} \quad (14)$$

In the actual control system, the actuation dynamics must be considered. With the force gradient servo, the aileron control input must be translated into a torque command. Nominally, assuming aileron position is available from an appropriate pickoff, this torque can be based on the positional error between the commanded aileron position and the actual position. This simple lateral control system then consists of the flight control law and the torque controller for driving

the servo, as shown in figure 32. In this case, where torque limiting is unnecessary, a simple proportional + integral + derivative (PID) controller is sufficient for the servo torque control law.

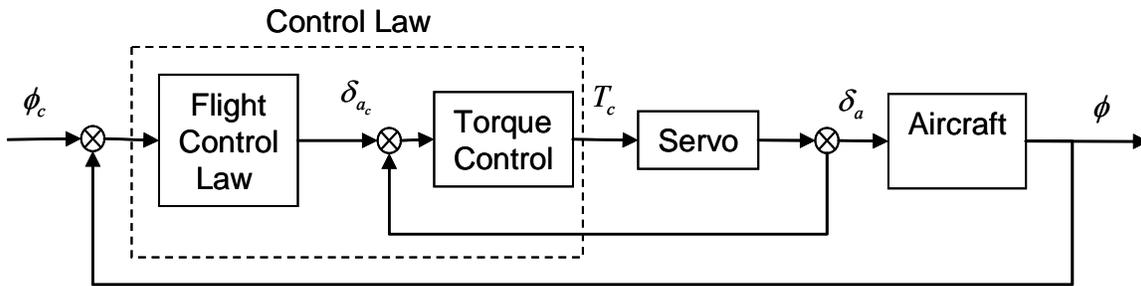


Figure 32. Control System With Torque Control and Servo Included

5.4.2 Lateral Stability Augmentation.

Stability augmentation can take a variety of meanings, and under the force gradient control concept, several concepts are possible. Consider the nature of light aircraft cruising without any pilot inputs on aileron. Most aircraft will drift in roll in one direction or another. Once in a banked condition, depending on the design, an aircraft will either have the tendency reduce the bank angle, hold the bank, or diverge to a larger bank angle. Often, this behavior is a function of numerous parameters, including magnitude of the bank angle itself, fuel loading, power settings, speed, and state of coordination. Therefore, in general, most light aircraft cannot be considered to be stable in roll. With one form of mild stability augmentation, it is possible for the aircraft to always have the tendency to return to a wings-level condition. In such a scheme, a control law would run in the background that constantly commands: $\phi_c = 0$.

The force gradient control concept is illustrated in figure 33. The aircraft pilot commands a rolling moment to the left by deflecting the aileron control. In turn, the ailerons and the actuator are moved. The ailerons immediately respond to the deflection with a stick force based on the associated aerodynamic hinge moments. The pilot must overcome this force to maintain the rolling moment. As the bank angle increases, the flight control senses the nonzero bank condition and commands the actuator to roll the aircraft in the opposite direction. However, the system is torque-limited so that it can provide only a small fraction of the actual hinge moment created by the ailerons themselves. The pilot must overcome this force too, but it is only a fraction of the actual aileron hinge moment. If the pilot relaxes the control, the aileron hinge moments restore the ailerons to a neutral position. Now the servo becomes the dominant actuator in the system, and it commands a restoring aileron command. However, it is limited by its own torque and the aileron hinge moments, so the amount of possible deflection is where the servo and the aileron hinge moments reach equilibrium. Hence, a much smaller aileron deflection is commanded, but one that is sufficiently large to tend to roll the aircraft to a wings-level condition and maintain it.

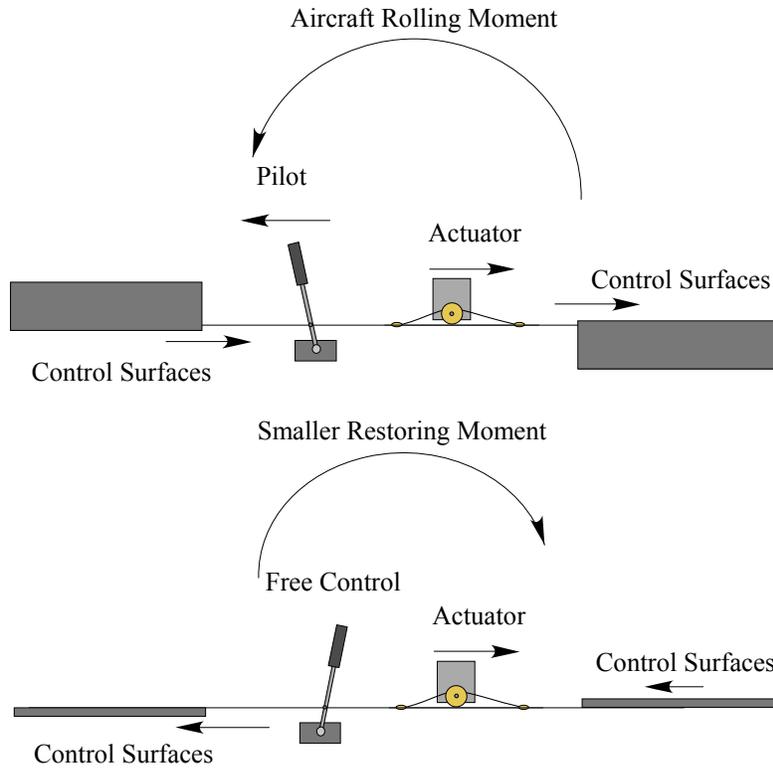


Figure 33. Stability Augmentation Functionality

Figure 34 illustrates all the forces applied to the aileron cable. First, based on control law, the flight control system commands an aileron deflection, δ_{a_c} . The torque control measures the aileron deflection error and commands an appropriate servo motor torque based on a proportional gain. However, a limiter in the torque control limits the allowable torque based on various parameters relative to aircraft speed and the aileron hinge moment. This commanded torque is sent to the servo and is applied to the spindle, resulting in a force on the control cable. Additionally, the pilot provides a force to the control cable. As the aileron deflects under the applied torque, the aerodynamic hinge moments resist the applied torques and an equilibrium position is reached.

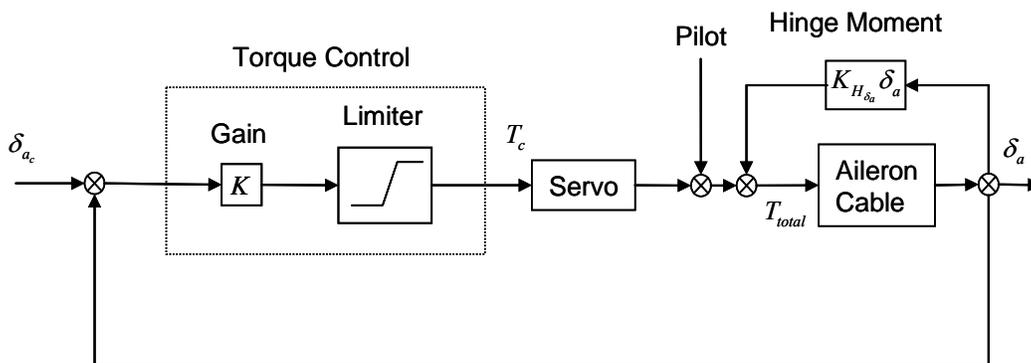


Figure 34. Applied Torques to the Aileron

In some cases, it may be appropriate for an aircraft to always tend to roll wings level. It may be more desirable for the aircraft to maintain a bank angle more precisely. In this case, a command of zero bank angle rate ($\dot{\phi}_c = 0$) may be appropriate. There are various forms of stability augmentation possible and worthy of consideration.

5.4.2.1 Aileron Hinge Moments.

With Force Gradient Control, the hinge moments play a key role in the development of the control laws. The control laws must consider the hinge moments, not only in terms of control authority but also in terms of pilot control ability. The servo torque has to be high enough to command a sufficient roll rate, but not so strong as to interfere greatly with pilot control, at least for the purpose of stability augmentation (envelope protection functions are discussed in section 5.4.3).

Figure 35 illustrates a simple wing control surface such as an aileron. Such a surface has a hinge moment influenced primarily by the aileron deflection angle δ_a . Equation 15 shows the aileron hinge moment expression. For a fixed dynamic pressure, the hinge moment is constant.

$$H_a = qS_a\bar{c}_a C_{h_{\delta_a}} \delta_a \quad (15)$$

where

- H_a = hinge moment about hinge line
- q = dynamic pressure
- S_a = area of control surface
- \bar{c}_a = chord of control surface to hinge line
- $C_{h_{\delta_a}}$ = hinge moment coefficient

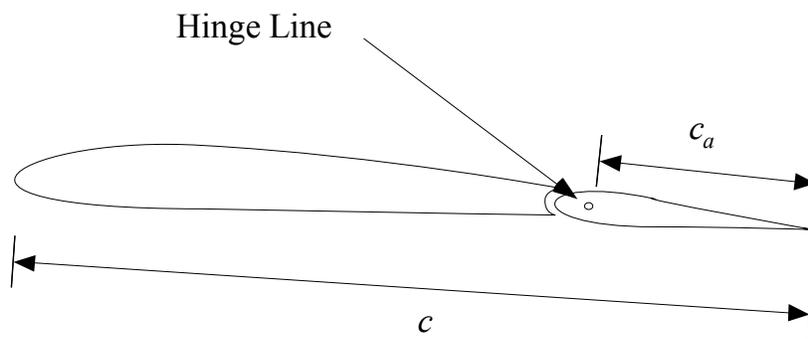


Figure 35. A Simple Aileron Control Surface

The rolling moment of the airplane is characterized by equations 16 and 17 where the term L is the rolling moment of the aircraft, which is a function of aileron and rudder deflections, along with other aircraft state parameters [9].

$$L = qS_w b_w C_l \quad (16)$$

where

S_w = wing area
 b_w = wing span

and the rolling moment coefficient is given by

$$C_l = C_{l_\beta} \beta + \frac{b_w}{2u_o} C_{l_p} p + \frac{b_w}{2u_o} C_{l_r} r + C_{l_{\delta_a}} \delta_a = C_{l_{\delta_r}} \delta_r \quad (17)$$

where

β = sideslip angle
 p = roll rate
 r = yaw rate
 δ_a = aileron deflection
 δ_r = rudder deflection
 u_o = reference forward speed

The stability and control derivatives are defined in table 3.

Table 3. The Rolling Moment Stability and Control Derivatives

Derivative	Definition
C_{l_β}	Sensitivity of rolling moment to sideslip
C_{l_p}	Sensitivity of rolling moment to roll rate
C_{l_r}	Sensitivity of rolling moment to yaw rate
$C_{l_{\delta_a}}$	Sensitivity of rolling moment to aileron deflection
$C_{l_{\delta_r}}$	Sensitivity of rolling moment to rudder deflection

In steady-state conditions, the rolling moment is dominated by the aileron contribution, so the expression can be approximated using aileron contribution only, as shown in equation 18.

$$C_l \cong C_{l_{\delta_a}} \delta_a \quad (18)$$

Including this expression, equation 16 yields an expression (equation 19) that is linear with the changes in aileron deflection.

$$L = qS_w b_w C_{l_{\delta_a}} \delta_a \quad (19)$$

Interestingly, the ratio of rolling moment to aileron hinge moment is largely independent of speed or aileron deflection.

$$\frac{L}{H_a} = \frac{S_w b_w C_{l_{\delta a}}}{S_a \bar{c}_a C_{h_{\delta a}}} \quad (20)$$

So, regardless of speed or resulting aileron deflection, a given applied aileron hinge moment will generate the same aircraft rolling moment.

At present, the best system for establishing torque limits for the servo is unclear. If the torque limit is to remain a fixed fraction of the total aileron hinge moment, then the torque values would need to vary with airspeed. In this manner, the torque would scale just as aileron hinge moments scale. If a constant rolling moment capability is desired, the torque limits must remain independent of airspeed. In this case, the stick force addition of the actuator would be more apparent at low speeds than at high speeds. A human factors analysis, ultimately including pilot-in-the-loop simulation and flight test of a prototype system, will likely be required to definitively address these design issues.

5.4.3 Lateral Envelope Protection.

In stability augmentation, the desire is for the control law to add stability while causing minimal interference in pilot operation. However, with envelope protection as envisioned here, the goal is for the control system to be continuously active, often providing control forces in opposition to pilot inputs, in such a way as to positively influence the resultant behavior of the combined pilot-airplane-autopilot system.

In a design approach, however, envelope protection differs little from stability augmentation in the lateral control case. In fact, lateral envelope protection could be provided as a direct extension of stability augmentation, with the only substantial difference being the amount of torque the servo is allowed to provide, as a function of the bank angle of the aircraft. Within certain safe limits, the control law would run in stability augmentation mode, but beyond a certain bank angle, maximum allowable servo torque would increase.

Figure 36 illustrates one possible torque limit profile, as a function of bank angle. Within a “safe” bank angle regime, the maximum allowable servo torque is kept at a low value, T_{stab} . However, once the safe bank angle is crossed, the limiter will allow greater and greater torques, T_{env} , as specified by the envelope protection control parameters. At large bank angles, the pilot will need to overcome the full available torque of the autopilot servos to deliberately maintain the bank angle. Presumably, during this time, visual and audible warnings will also warn the pilot of the condition.

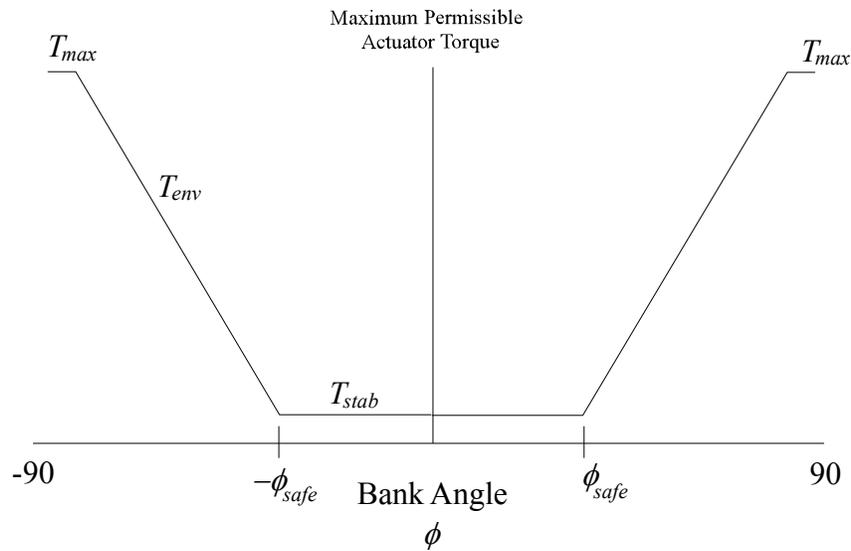


Figure 36. Conceptual Plot of Allowable Servo Torque vs Bank Angle

5.5 FORCE GRADIENT METHODS APPLIED TO LONGITUDINAL CONTROL.

In the Force Gradient Concept, the flight controller behaves as a conventional autopilot when explicit autopilot functionality is activated, but remains engaged even when explicit autopilot functionality is deactivated. As with the lateral control scheme, longitudinal flight control is divided into three categories: conventional autopilot functionality, stability augmentation, and envelope protection.

5.5.1 Longitudinal Conventional Autopilot Functionality.

Longitudinal autopilots control the pitch and the speed of the aircraft. For light GA aircraft, autothrottle capability is not yet commonly available, so the autopilot uses elevator inputs exclusively to control the aircraft.

Depending on the mode of operation, the elevator control is used to control either the pitch or the speed of the aircraft, with pitch control the more common of the two. Higher-level functions, such as altitude hold, altitude capture, and vertical speed control, are all implemented as outer loops that depend on the inner loop function of pitch control. This section concentrates on how a desired elevator deflection can be achieved from the perspective of servos and control surface hinge moments rather than on how a longitudinal control law is obtained with satisfactory stability and responsiveness. For the purpose of this discussion, a simple pitch control law is implemented, as shown in figure 37.

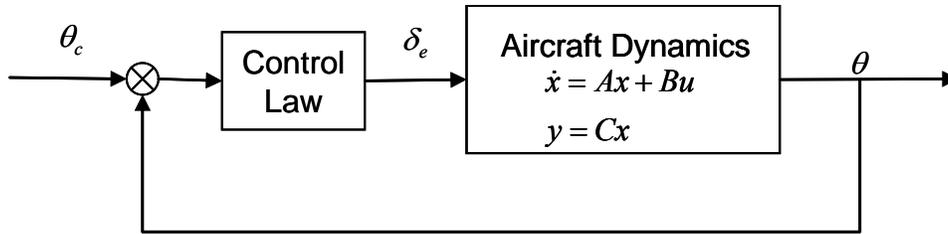


Figure 37. Basic Longitudinal Control Law

5.5.1.1 Aircraft Trim and Elevator Hinge Moments.

Longitudinal control differs from lateral control in that there is not a fixed, steady-state condition analogous to the wings-level condition in the lateral system. Rather, the aircraft has to be trimmed for a particular flight condition by maintaining a steady-state AOA, which in general, requires some continuous, nonzero elevator deflection. This relationship is expressed in equation 21, where the required elevator deflection for a steady-state AOA is expressed in terms of the appropriate stability and control derivatives.

$$\delta_e = \frac{-(C_{m_0} = C_{m_\alpha} \alpha)}{C_{m_{\delta_e}}} \quad (21)$$

In aircraft with reversible controls, the control system requires a constant stick force to maintain an elevator deflection. To alleviate the continuous stick force, most aircraft are trimmed using a mechanism that actuates a small trim tab on the elevator surface, as shown in figure 38. The trim mechanism manually holds the trim tab in a fixed location relative to the elevator surface and relieves the need for constant stick force.

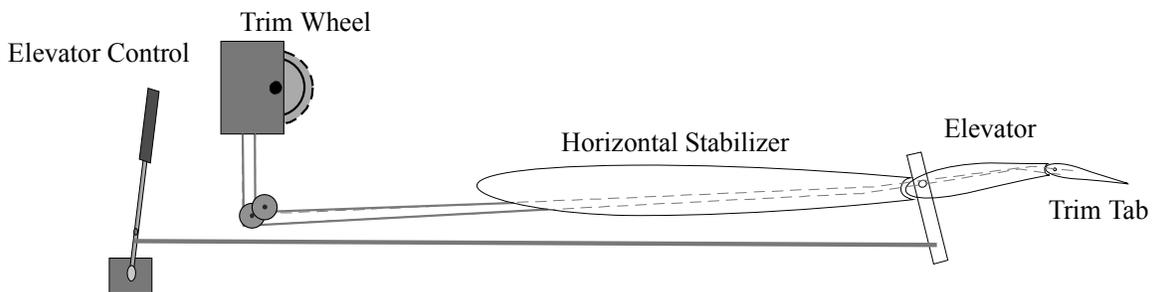


Figure 38. Elevator Control Along With Trim Mechanism

The trim tab changes the camber of the elevator so the surface finds a new equilibrium. In practice, the pilot trims the aircraft for a given flight condition using the trim tab, and then uses the flight control to make minor adjustments in response to disturbances. The elevator nomenclature is illustrated in figure 39.

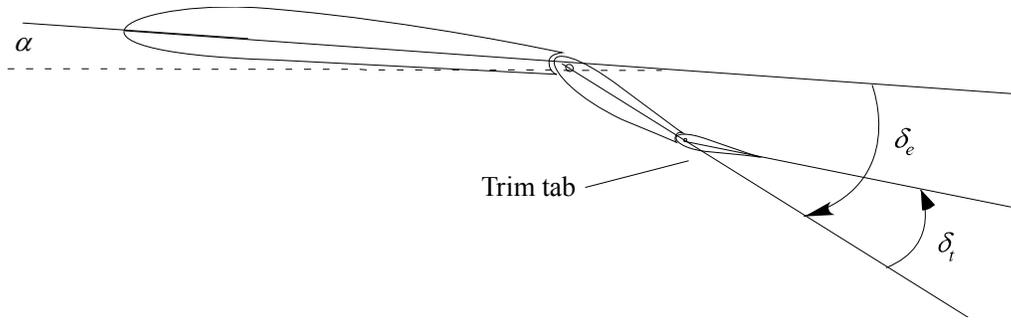


Figure 39. Elevator Nomenclature Definition

The elevator hinge moment is characterized as a function of dynamic pressure, the area of the elevator surface, S_e , the elevator chord, c_e , and the moment coefficient, C_{h_e} .

$$H_e = qS_e c_e C_{h_e} \quad (22)$$

The elevator hinge moment coefficient is in turn a function of the local AOA at the tail, α_1 , the elevator deflection, δ_e , and the deflection of the trim tab, δ_t .

$$C_{h_e} = C_{h_0} + C_{h_a} \alpha + C_{h_{\delta_t}} \delta_t \quad (23)$$

For a given AOA and elevator deflection combination, the pilot or flight control system should adjust δ_t such that the hinge moment coefficient is close to zero.

5.5.1.2 Autopilot Block Diagram.

The actuation of a particular elevator command takes on added complexity in the presence of the force gradient servo and the need to trim the elevator surface. Figure 40 shows the major components of the system. The basic control law controls pitch using elevator deflection. To achieve a desired elevator deflection, a motor torque for the main elevator servo is commanded. Once a torque is commanded, the servo torque and the elevator hinge moments both act on the elevator surface to move it to the equilibrium position.

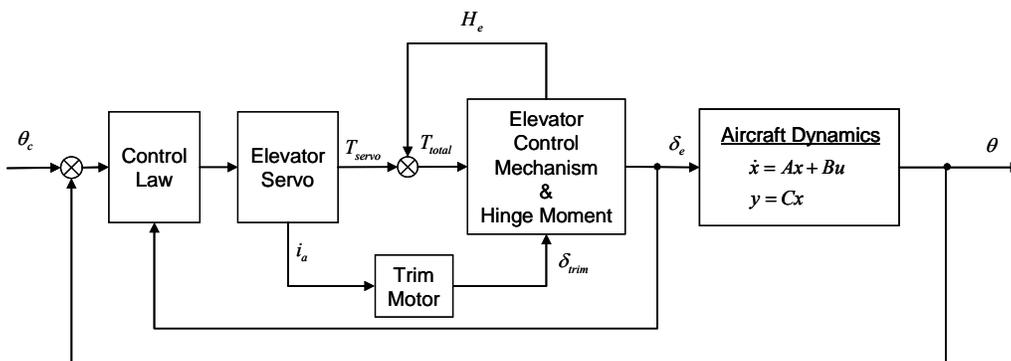


Figure 40. Autopilot Block Diagram

Providing that the elevator servo has sufficient power to overcome the hinge moments, it can command and maintain the appropriate elevator deflection for the commanded pitch angle. However, it is not desirable for there to be a constant load on the servo motor, so a trim motor, which is just a DC motor, is engaged to move the elevator trim tab to an appropriate location. The trim motor is actuated by a measurement of the elevator servo current. Since current flow through the servo is an indication of its load, the trim servo uses the current measurement (not the current itself) as a signal to drive the trim wheel. As the trim wheel is moved, the load and hence the current, on the elevator servo will be reduced. In trim, the servo load should be close to zero.

Fast dynamics are not necessary for the trimming operation to achieve its objective (relieving the main elevator servo of the need to hold a continuous load). Therefore, the trim motor control can be very simple on/off logic, whereby the motor is triggered by a main elevator servo current greater than a specified value and just runs in the direction of relieving load on the main elevator servo. Of course, care must be taken to ensure that the nonlinear dynamics of the trim system do not result in limit cycling or other untoward effects on the primary pitch control of the aircraft. In addition, the main elevator control law must take into account the state of elevator trim in order to command an appropriate main servo torque to achieve any particular desired elevator deflection.

Figure 41 shows a more detailed look at the elevator control system. As with the lateral system, the control law consists of two major components, the flight control and the torque control. The flight control contains the control laws classically associated with aircraft control. In this case, a hypothetical PID controller takes the pitch error signal and determines a desired elevator deflection. The elevator command is fed to the torque controller, which determines the required torque using elevator position error. Since there is a $1/s^2$ relationship between torque and position, it is possible a single gain control may suffice. The elevator position is measured in terms of shaft position by sensors on the servo, with a means of verifying the correct zero position when the system is initially turned on.

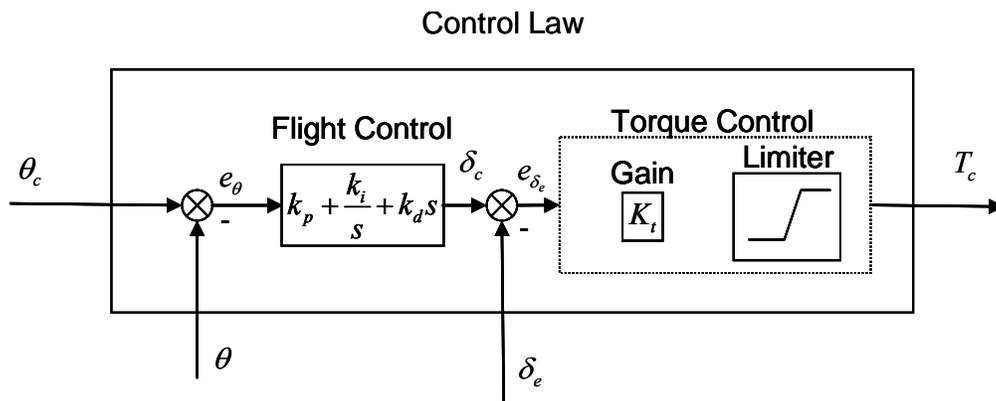


Figure 41. Detailed View of Control Law

5.5.2 Longitudinal Stability Augmentation.

In the lateral case, where a wings-level condition was a clear desired state, zero bank angle is an obvious default control system set point. In the longitudinal case, there is no such nominal pitch angle that is appropriate for most flight conditions. While an aircraft may spend most of its time in level flight, aircraft also climb and descend. Furthermore, even level flight does not indicate a zero-pitch attitude condition. Pitch is a function of the flight path angle and the AOA, which in turn for unaccelerated flight, is a function of aircraft weight and speed. Most longitudinal aircraft parameters vary with the trim condition, so no single pitch angle exists as a default control system goal. Rather, an outer loop set point for longitudinal control is generally established by virtue of some performance goal other than pitch per se, such as such as rate of climb or descent or airspeed.

For stability augmentation, since the dominant mode, the phugoid mode, is stable but lightly damped, it is desirable to add some light damping to the system. Pitch angular rate becomes an important quantity in providing additional longitudinal stability in this case. Figure 42 shows an example of feedback architecture. With this type of longitudinal stability augmentation active, the desired trim condition can still be manually set by the pilot through the trim wheel, and the aircraft will simply exhibit an enhanced tendency to maintain a stable condition in pitch.

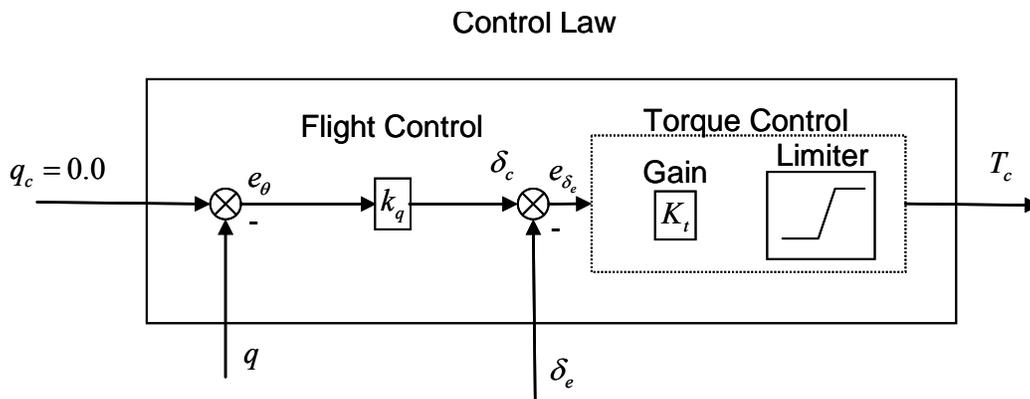


Figure 42. Potential Stability Augmentation Involving Simple Pitch Rate Feedback

As with lateral stability augmentation (outside the envelope protection realm,) the longitudinal stability augmentation is limited so that it can only apply a small amount of torque to the surface. This way, the torque effects of the added damping are easily overcome by the pilot during manual flight control tasks. The nature of the limit is still a matter for future research.

5.5.3 Longitudinal Envelope Protection.

Envelope protection in the longitudinal sense is perhaps the most critical of all operations, since exceeding the critical AOA is a necessary factor for all stalls and stall spin accidents.

Unlike the lateral system, longitudinal envelope protection is not a simple variation of the stability augmentation mode. In longitudinal envelope protection, there are at least four critical conditions to protect against. These are:

- Exceeding critical AOA
- Excessive g forces
- Overspeed
- Excessive pitch angles

For AOA and g-force reduction, the force gradient control works in a straightforward way to provide envelope protection in a manner that is not likely to be surprising or disconcerting to the pilot. Forces can be applied in a smoothly increasing fashion to alleviate the abrupt nature of conventional actuators suddenly being activated.

However, in the excessive pitch and overspeed cases, pilot control interactions may be more subtle and complex. In both cases, a more complex flight control strategy is needed to resolve the dangerous situation, primarily because large changes in aircraft energy state are involved. Planning for an entire trajectory segment may be required in extreme cases, and a larger degree of servo command authority may be required at the onset of intervention to successfully recover the aircraft to straight-and-level flight.

The potential interactions between the pilot and the envelope protection system in recovering from an overspeed or excessive pitch flight condition may prove to be very important to the overall design. This area requires future research to determine how best to use the force gradient concept. Some initial thoughts are presented in the following sections.

5.5.3.1 Critical AOA.

The physical relationship between the elevator deflection and AOA is governed by the short period mode, which is a well-behaved, second-order mode with good damping and a frequency typically 10 times faster than the phugoid longitudinal mode. Essentially, at short-period frequencies, there is a direct relationship between AOA and the elevator. Additionally, the hinge moments on the elevator always act in the direction of reduced elevator deflection, which implies that a reduction of backpressure on the elevator flight control will always reduce AOA. This reduction is obtained quickly, and in aircraft with good flight characteristics, without excessive oscillation (figure 43).

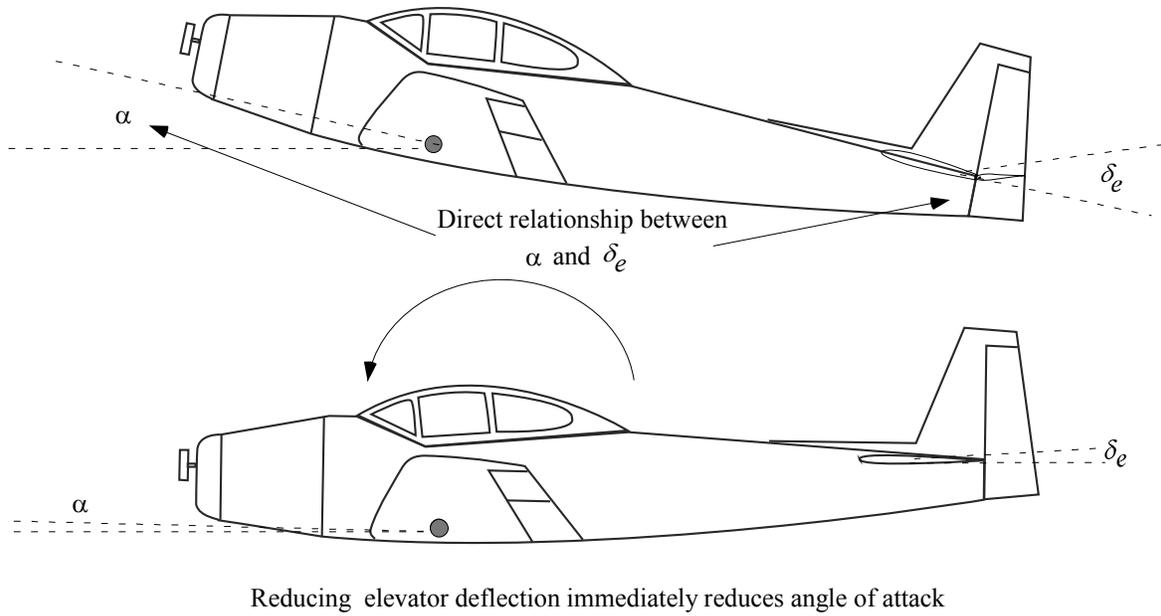


Figure 43. Direct Relationship Between Elevator Deflection and AOA

To implement protection against exceeding critical AOA, a variation on the stick pusher concept can be used. As opposed to a classical stick pusher implementation, however, the variable torque capabilities of the force gradient servo can be exploited so that the applied load is introduced gradually and has a continuous feel to the pilot.

In this concept, a safe AOA is defined, α_{safe} , which is the maximum AOA that the pilot should command without any intervention from the aircraft. This AOA would likely be a few degrees less than the critical AOA. Once the safe AOA is exceeded, the envelope protection system would apply a torque to the control system to reduce elevator deflection. This torque would be proportional to the AOA in excess of the safe value. The relationship is described in equation 24. Beyond the critical AOA, the system continues to apply torque, until the maximum servo torque is applied. Figure 44 illustrates the relationship between AOA and envelope protection torque.

$$T_{env} = K_{T_{env}} (\alpha - \alpha_{safe}) \quad (24)$$

When the pilot responds and reduces the elevator back pressure, the system responds by unloading the torque proportionally to the reduction in AOA. Once AOA is reduced below α_{safe} , no more torque is applied.

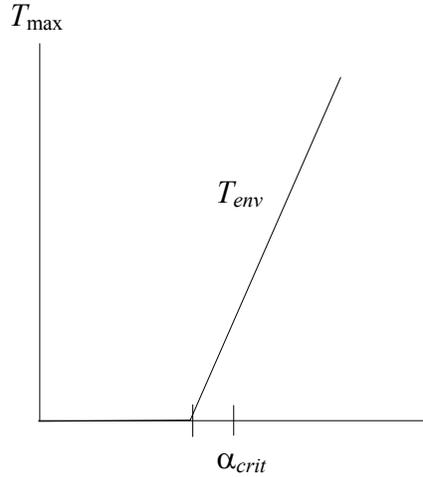


Figure 44. Envelope Protection Torque as a Function of AOA

5.5.3.2 Excessive g Forces.

The same type of protection used for AOA can be used for g-force protection. Equation 25 shows that the g force is the ratio between lift and weight, and g-force increases are proportional to AOA. Excessive g force can be dealt with using a proportional scheme similar to the one used for AOA, as shown in equation 26 and figure 45.

$$n_z = \frac{qS_w (C_{L_o} + C_{L_\alpha} \alpha)}{W} \tag{25}$$

$$T_{env} = K_{T_{env}} (n_z - n_{z_{safe}}) \tag{26}$$

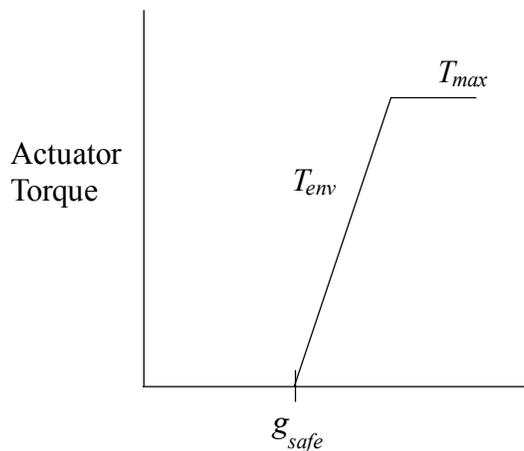


Figure 45. Envelope Protection Torque as a Function of g Force

5.5.3.3 Overspeed.

Overspeed is the condition where the aircraft is exceeding the posted redline speed for the aircraft. This is most likely to happen in a descent. In this case, the envelope protection needs to command an increased AOA to make the aircraft decrease its rate of descent and, hence, reduce speed. This is an interesting scenario because, in this case, the elevator command has to be in the opposite direction of the g force and AOA schemes and in the opposite direction of the naturally occurring elevator hinge moments.

It is instructive to consider how this problem differs from the AOA problem from a human factors' perspective. In the AOA case, the increased forward pressure on the stick is intended to prevent the pilot from commanding a critical AOA and to encourage the pilot to release stick pressure. If the pilot complies or even lets go completely, the aircraft's AOA is reduced, and envelope protection can be disengaged.

In the case of overspeed, the pilot may be already holding some backpressure in the descent. In this case, the envelope protection will add additional backpressure and may literally lift the control yoke out of the pilot's hands. Since the hinge moments are in the opposite direction of the applied torque, the pilot's release of backpressure could increase the overspeed. If a pilot lets go in this case, the envelope protection will be now flying the aircraft completely, and must be prepared to (1) provide enough torque to actuate the surface, (2) stabilize the aircraft and return it to a safe speed.

Figure 46 shows one potential feedback control strategy. In this case, a proportional + integral (PI) controller is used on speed error, along with some pitch rate feedback, which is usually required for additional damping. What is still not clear, however, is what kind of torque limiting should be applied to ensure that the pilot feels a gradual transition as the envelope protection effectively takes control of the aircraft. Additionally, it is not clear when the system should activate and deactivate. One possibility is to engage the system at some speed close to redline and disengage it once a safe speed is regained.

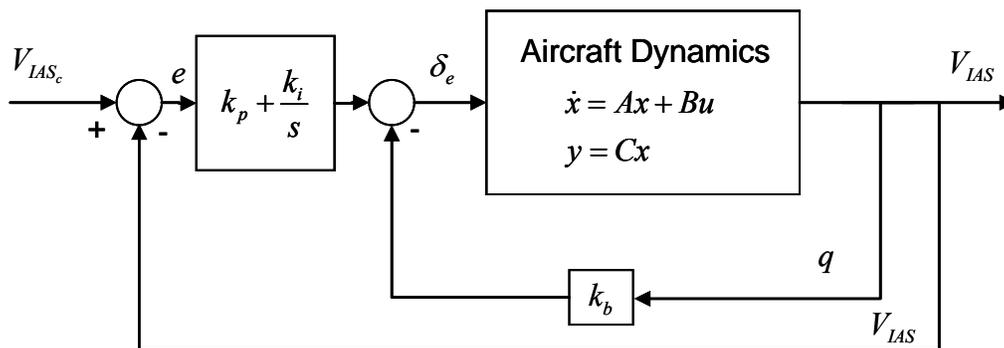


Figure 46. Potential Feedback Control Strategy for Commanding Speed

5.5.3.4 Excessive Pitch.

Excessive pitch is a difficult scenario to handle since the pitch is governed by the phugoid mode, which is the slower of the two longitudinal modes. The phugoid mode represents the gradual interchange between potential and kinetic energy about some equilibrium altitude and airspeed and manifests itself through changes in pitch attitude, altitude, and velocity at a nearly constant AOA (see figure 47).

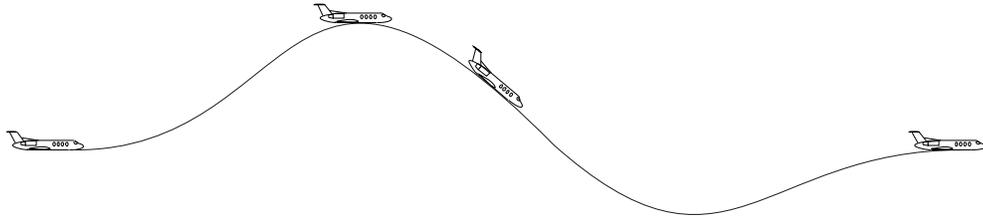


Figure 47. The Phugoid Mode

In the case of excessive pitch, it would be insufficient to reduce elevator deflection through a simple proportional control law because this would only aggravate the natural dynamics of the phugoid. Consider a scenario where a pilot inadvertently pulls the aircraft into a high-pitch state and at the onset of envelope protection activation, the disoriented pilot releases the control yoke. The immediate release of elevator only serves to greatly excite the phugoid, causing additional oscillations in pitch. Therefore, a more sophisticated feedback control for pitch envelope protection is needed.

Figure 48 shows a potential control scheme for excessive pitch envelope protection. In this law, PI control is used on pitch error, and pitch rate feedback is used to stabilize the mode. Such a law is relatively straightforward, but what is not obvious is how and when it should be activated.

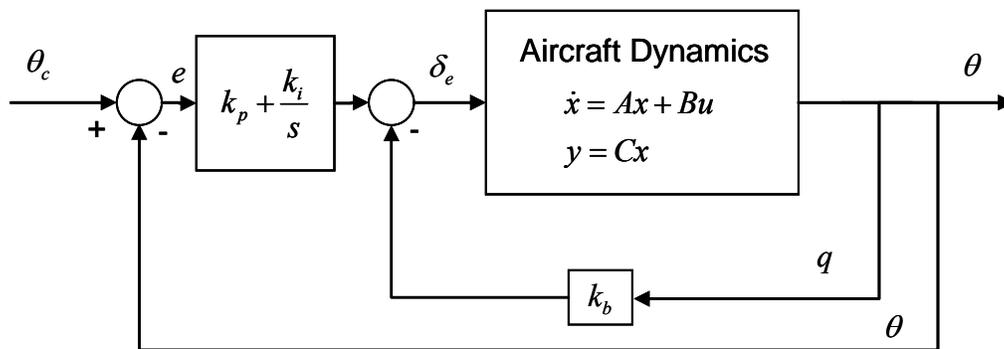


Figure 48. A Pitch Command Control Law for Pitch Envelope Protection

It is assumed that if the pitch angle magnitude becomes extreme, the system should engage. However, what is not clear is when and in what manner it should disengage. Simply fully disengaging at some predefined pitch angle is probably insufficient, because if high pitch oscillations are present, the law will switch off the first time it traverses through its disengage point, and will fail to stabilize the aircraft. Therefore, some bound on pitch rate is probably also

required within the mode-switching logic to determine when to disengage the envelope protection feature.

Additionally, it would be undesirable to have the system deactivate while there is still substantial main elevator servo torque required to maintain the current commanded elevator position (i.e., before the elevator trim function has had sufficient time to unload the main servo), because disengaging at such a time might serve only to re-excite the phugoid dynamics. For the present, the question of precisely when and how to disengage must be left as a subject for future research.

5.5.3.5 Envelope Protection Flow Diagram.

For longitudinal control, the four components of envelope protection described thus far cannot be implemented in isolation. In some flight situations, multiple goals that are potentially conflicting may need to be simultaneously pursued. For example, an overspeed situation may involve exceedences of desired speed, g force, and pitch limits simultaneously. Therefore, a general system for continuously evaluating the aircraft state and arriving at an appropriate control law objective for all potential flight circumstances must be synthesized.

One potential hierarchy for control would consist of the following prioritization of control system goals, with the most important goal first:

- Maintain airframe loading within limits (avoid over-g)
- Maintain AOA within limits
- Maintain airspeed within limits (avoid overspeed)
- Maintain pitch within limits

Simply applying the appropriate envelope protection control modes to each goal in sequence, ignoring lower-priority goals until higher-priority ones are met, yields an appropriate and effective control architecture for longitudinal envelope protection.

6. CERTIFICATION OF ENVELOPE PROTECTION SYSTEMS.

This section explores the certification basis for a light aircraft envelope protection system. Since there is no explicit precedent for envelope protection systems for light aircraft, the certification basis is constructed from existing regulations for systems that share some similar aspects to an envelope protection system.

Envelope protection systems as defined in this report have three potential levels of functionality. These levels of functionality are:

- Supplemental advisory-only systems
- Advisory systems that also function as certificated stall warning equipment
- Envelope protection systems that offer active protection

6.1 REGULATORY BASIS.

The CFRs that are most likely to comprise the certification basis for envelope protection systems for light aircraft are as follows [10]:

- 14 CFR Part 1—Definitions and Abbreviations
- 14 CFR Part 21—Certification Procedures for Products and Parts
- 14 CFR Part 23—Airworthiness Standards: Normal, Utility, Acrobatic, and Commuter Category Airplanes
- 14 CFR Part 43—Maintenance, Preventative Maintenance, Rebuilding, and Alteration
- 14 CFR Part 91—General Operating Flight Rules

6.2 METHODS OF CERTIFICATION.

There are several methods of approval for parts and components for aircraft. Usually, avionics are certified under a Technical Standard Order (TSO), Supplemental Type Certificate (STC), or less likely, under Parts Manufacturer Approval (PMA).

Approval under a TSO (14 CFR 21.601-21.621) is common. The FAA has adopted numerous TSOs to cover a wide range of devices, so if the device in question matches the functionality described in a TSO, the certification basis is straightforward. The TSO does not grant approval for installation on a particular aircraft, but it provides data to support such an installation. Installation is accomplished through an STC or a field approval [10].

An STC (14 CFR 21.111-21.119) is granted to modify the design of an existing aircraft. Avionics installation is often handled with an STC. First, the applicant must determine the certification basis of the aircraft to be modified, which is generally established by the aircraft's Type Certificate Data Sheet. The next step is to negotiate the certification basis of the modification with the FAA. In cases where an existing TSO or CFR is directly applicable, this task may be straightforward. However, in cases where a unique or unusual product is proposed, a special condition (14 CFR 21.16) issue paper may be required. Issue papers are developed to address novel or unusual design features for which there are no regulations or inadequate regulations. These issue papers are used for development of the basis, need, and wording of special conditions. A special condition contains only such airworthiness standards as are necessary to establish a level of safety equivalent to that established by the intent of the applicable regulations. Special conditions are unique to the specific certification program in which they are issued, unless by special statement in the special condition [11].

If a component is not produced under a TSO or a type certificate (supplemental or otherwise), PMA (14 CFR 21.301-21.305) applies. Generally, PMA applies to replacement parts that are identical to the original parts, where the part number and original drawings and data can be referenced. However, there is some precedent for modifications to be granted PMA without either a TSO or STC.

6.3 SUPPLEMENTAL ADVISORY SYSTEMS.

Most light aircraft have some single-position, stall warning sensor that sounds a buzzer once a particular flight condition is reached. A supplemental system would likely provide some continuous indication of AOA and perhaps additional coordination information. Such a system would not legally take the place of any certificated stall warning system, but it could provide the pilot with a much clearer indication of the aircraft's flight condition.

Currently, several manufacturers have products that provide some type of supplemental stall warning. One example is the InAir Lift Reserve Indicator [12]. InAir Instruments, LLC is a small company that has been producing a Lift Reserve Indicator since the mid 1980s. The product uses differential pressure off a two-port pitot tube to determine the lift reserve. The differential pressure is indicated on a gauge in the cockpit. The instrument provides an indirect measurement of AOA and is shown in figure 49.



Figure 49. Lift Reserve Indicator Head

The InAir product does not really qualify as avionics since it contains no electronics. Rather, it is a pressure gauge attached to a special pitot tube. The InAir Lift Reserve Indicator is not TSO'd or STC'd for any aircraft or application, but is still installed in certified aircraft, per the permission of the local Flight Standards District Office (FSDO), as shown in a letter from the San Jose FSDO (figure 50).



U.S. Department
of Transportation
**Federal Aviation
Administration**

San Jose Flight Standards District Office

San Jose International Airport
1250 Aviation Avenue, Suite 295
San Jose, CA 95110-1130
Phone: (408) 291-7581
FAX: (408) 279-5448

July 30, 1999

Bill Geipel
467-A 95th Street
Clear Lake, WI 54005

Dear Mr. Geipel:

Our office received an inquiry with regards to the Lift Reserve Indicator's need for FAA Form 337 Field Approval.

Our Airworthiness Unit carefully reviewed the Lift Reserve Indicator's pamphlet, Federal Aviation Regulation Part 43, and Advisory Circular 43.9-1E. In our office opinion, we have concluded that installation of the non-heated Lift Reserve Indicator does not require a FAA Form 337 Field Approval. However, an entry into the aircraft maintenance log is required to complete the task.

If a heated type Lift Reserve Indicator is installed on an aircraft, a FAA Form 337 Field Approval would be required due to utilization of the aircraft's electrical system.

If we can be of further assistance, call (408) 291-7681 extension 136.

Sincerely,

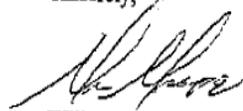

For Wilbert J. Robinson, Jr.
Aviation Safety Inspector

Figure 50. Installation Approval for Lift Reserve Indicator

The installation of this instrument, as specified by the approval letter, is not a basis for any kind of certification, but rather an approval to install, presumably since the instrument performs no legal function. The inspector does not consider the suitability of the instrument for its intended purpose, but rather consults 14 CFR Part 43 and Advisory Circular (AC) 43.9-1E as a basis for installation approval. 14 CFR Part 43 addresses maintenance and airworthiness standards. While the approval letter does not explicitly state it, the inspector most likely is consulting Appendix A of 14 CFR Part 43 that documents what constitutes a major repair or alteration. Since the basic instrument does not have any structural, electrical, or navigation significance under 14 CFR Part 43, its installation is considered a minor alteration. Therefore, the inspector determines that this instrument (which is not covered in a TSO) can be installed with as little as a

mechanic's endorsement. However, in the inspector's judgment, a version of the instrument with a heater element would constitute a major alteration because of the alteration to the aircraft's electrical system. AC 43.9-1E details the proper procedure for filing a Form 337 but does not really provide any guidance in this particular instance. Either way, the instrument is installed on a field-approval basis.

This type of installation is unclear within the CFRs. In this particular case, the Administrator appears to take a benevolent stance towards the installation of these instruments as a field approval. However, if one were to apply the strictest possible interpretation of the CFRs, the installation of the Lift Reserve Indicator would appear to violate 14 CFR 21.303(a) (see figure 51), which states that PMA is required for any part installed on a certificated product. In this particular case, the judgment appears to have been made that PMA is not required, given the use of the Lift Reserve Indicator as an advisory-only system that does not take the place of existing aircraft instruments or systems.

Sec. 21.303 Replacement and modification parts.

(a) Except as provided in paragraph (b) of this section, no person may produce a modification or replacement part for sale for installation on a type certificated product unless it is produced pursuant to a Parts Manufacturer Approval issued under this subpart.

(b) This section does not apply to the following:

- (1) Parts produced under a type or production certificate.**
- (2) Parts produced by an owner or operator for maintaining or altering his own product.**
- (3) Parts produced under an FAA Technical Standard Order.**
- (4) Standard parts (such as bolts and nuts) conforming to established industry or United States specifications.**

Figure 51. 14 CFR 21.303

For an action to be judged in violation of 14 CFR 21.303, it appears that a major alteration must be contemplated, and the manufacturer of the part must sell the product with the intent that it be installed on certified aircraft. Consider the case involving B&C Specialty Products, and the FAA enforcement action taken against them [13]. B&C Specialty Products sold alternators to the home-built market but, occasionally, would sell alternators for installation on Piper Super Cubs. These alternators were commonly approved under individual field approvals. The company explained to customers that it was not a PMA part, and that it was the customer's responsibility to obtain a field approval for the installation. However, the company was also in the habit of providing sample field approvals from prior installations, making perpetual field approval the basis for the installation of the alternator. After approximately 60 such field approvals had been performed, the FAA proposed a fine against B&C for being in violation of 14 CFR 21.303. While the enforcement action was eventually dropped, the scenario points out the precarious nature of perpetual field approvals as a means of certification. Recently, the B&C alternator system was granted an STC (see figure 52) [14].



Figure 52. B&C Specialty Products Alternator

It is also instructive to note that even benign devices such as sun visors and air vents (see figure 53) are commonly STC'd [15 and 16].



Figure 53. Rosen Sun Visors and Vent Tubes are STC'd

A more formal certification basis for an advisory-only system that includes AOA measurement is found in TSO-C54, "Stall Warning Instruments." TSO-C54 provides little guidance beyond referring the designer to SAE AS403A, "Stall Warning Instrument," where the real specification is contained. AOA sensors are certificated under this TSO, as TSO-C54 makes reference to both single operating point and continuous operating sensors, which are alpha-sensing devices. However, the InAir Lift Reserve Indicator device is not really a stall warning device or an AOA indicator. It is purely supplemental.

Given these circumstances and the arduous requirements of TSO-C54 for continuous stall warning devices, it may be more sensible to pursue a PMA without addressing a TSO or STC. There is some precedent for such alterations, although they are rare. Consider the Reiff preheat systems (see figure 54). The Reiff system is a preheater that attaches to an engine and plugs into an electrical outlet [17]. The preheater, which never operates when the engine is running, was deemed to be a minor alteration and therefore no STC or field approval (Form 337) was required. The part is PMA through the Chicago Aircraft Certification Office (ACO).



Figure 54. Reiff Preheat Systems

The Basic Advisory System described in this report differs from the InAir Lift Reserve Indicator system, in that it has multiple sensors that are tied into a microprocessor along with a electronic display. The electronic nature of the product may complicate the certification beyond what would be required for the InAir instrument. The judgment would largely hinge on whether the instrument would ultimately be considered a minor or major alteration under the guidance of 14 CFR 43 Appendix A. If it can qualify as a minor alteration, it might achieve PMA without needing an STC or field approval for installation.

6.4 CERTIFICATED STALL WARNING EQUIPMENT.

If the advisory system is to replace the original equipment manufacturer (OEM) stall warning equipment, the certification basis must be more stringent. Since the installation would have to be tailored for each individual aircraft type to ensure proper stall detection, an STC would certainly be required for the installation.

With respect to certification basis, the obvious place to start is 14 CFR 23.207 and TSO-C54. TSO-C54 references SAE AS403A, where the real specification is contained. SAE AS403A contains two different certification levels: the first level is for single-point operation warning systems, and the second is for continuous warning systems. The single-point system operates a warning upon exceedance of a particular AOA, whereas the continuous device is really a continuous AOA sensor in addition to a stall warning device.

While the Basic Advisory System is effectively a continuous system, it would be more convenient to certify it as a single-point operation system. TSO-C54 requires different environmental tests for the two types of instruments. The continuous system would have to work up to 40,000 ft and meet stringent de-icing criteria, neither of which is required for the single-point unit. It is clear that the single-point system certification requirements are tailored for smaller, lower-performance aircraft, and since the original equipment on most of the target aircraft have single-point operation systems, it is likely adequate for the STC.

Therefore, the Basic Advisory System would be TSO'd as a single-point unit, but it would have many features beyond that limited capability. These features would not necessarily have to be covered explicitly under a TSO. However, since the instrument would contain both a microprocessor and software, it would have to be developed in accordance with the appropriate RTCA documents. In this case, DO-178B, "Software Considerations in Airborne Systems and Equipment Certification," is appropriate for software, and DO-160E, "Environmental Conditions and Test Procedures for Airborne Equipment," would be appropriate for the hardware.

An instrument with a similar certification basis is the JP Instruments engine monitor series (see figure 55). This instrument is widely used for engine monitoring and performs many functions, including features to determine optimal lean settings, long-term trend monitoring, and data collection. While it has many features, ultimately, its certification basis, TSO-C43B, is a temperature sensor. No other features are explicitly covered by TSO. However, its computer hardware and software are certified under DO-160E and DO-178B (level C) respectively, and it is also STC'd (SA 2586NM) [18].



Figure 55. JP Instruments EDM-700

Interestingly, the newest version of the TSO, TSO-C43C, actually contains language that references DO-178B and DO-160E. If TSO-C54 is ever revised, it will likely contain similar language.

6.5 ENVELOPE PROTECTION SYSTEMS.

Active envelope protection systems are anticipated to meet the definition of supplemental systems, since they will be applied to existing type-certificated airplanes, and their functionality would not be essential for meeting basic certification requirements for those airplanes.

There is no existing set of certification rules that applies specifically to envelope protection systems as envisioned in this document. However, certain principles articulated in the standards for closely related systems, such as autopilots and artificial stall barrier systems, do apply to the proper design of any envelope protection system. These standards represent good engineering design practices and can be used to inform a negotiated certification basis for envelope protection

systems. Chief among the principles that form the basis for the existing standards are the following:

- Failures Nonhazardous—The system should not endanger the aircraft in the case of a system failure.
- Failures Not Concealed—Failures of system components should not be latent, i.e., they should be recognized and made clear to the pilot.
- No Misleading Behaviors—The system should not behave in ways that are likely to confuse the pilot as to the status or current operational modes of the system.
- Easily Disengaged—The pilot should be able to disable and/or override the systems in all cases to assert manual control of the aircraft.

The design of an envelope protection system should certainly adhere to these good design practices.

Portions of the following certification standards may be considered valuable in the context of generating a certification basis for envelope protection systems.

6.5.1 Autopilot Certification Standards.

Autopilots that include envelope protection features will naturally adhere to the basic autopilot regulations. Certification basis for autopilots is defined by 14 CFR 23.1329, “Automatic Pilot System,” and TSO-C9c, “Automatic Pilots,” which refers to SAE AS402B as its source for minimum performance standards. It should be noted that these regulatory instruments do not address the always-on automatic intervention features of an envelope protection system that do not have an explicit regulatory basis.

Always-on systems on light aircraft do have at least one precedent. Early model Mooneys came with a full-time wing leveler, named the Positive Control (PC) system. A thumb switch on the yoke was depressed to allow maneuvering, so it was not an automatic intervention system per se, but it does demonstrate a unique application of an automatic pilot system [19]. The original certification basis of these systems is not known, but it is assumed that it could be certified under TSO-C9c along with other autopilots.

The text of 14 CFR 23.1329 is shown in figure 56. The basic principles of good engineering design listed above are exemplified by many of the standards of 14 CFR 23.1329 (as well as by a number of the nonenvironmental functional aspects of SAE AS402B not reproduced here.)

Sec 23.1329 Automatic pilot system.

If an automatic pilot system is installed, it must meet the following:

(a) Each system must be designed so that the automatic pilot can—

(1) Be quickly and positively disengaged by the pilots to prevent it from interfering with their control of the airplane; or

(2) Be sufficiently overpowered by one pilot to let him control the airplane.

(b) If the provisions of paragraph (a)(1) of this section are applied, the quick release (emergency) control must be located on the control wheel (both control wheels if the airplane can be operated from either pilot seat) on the side opposite the throttles, or on the stick control, (both stick controls, if the airplane can be operated from either pilot seat) such that it can be operated without moving the hand from its normal position on the control.

(c) Unless there is automatic synchronization, each system must have a means to readily indicate to the pilot the alignment of the actuating device in relation to the control system it operates.

(d) Each manually operated control for the system operation must be readily accessible to the pilot. Each control must operate in the same plane and sense of motion as specified in §23.779 for cockpit controls. The direction of motion must be plainly indicated on or near each control.

(e) Each system must be designed and adjusted so that, within the range of adjustment available to the pilot, it cannot produce hazardous loads on the airplane or create hazardous deviations in the flight path, under any flight condition appropriate to its use, either during normal operation or in the event of a malfunction, assuming that corrective action begins within a reasonable period of time.

(f) Each system must be designed so that a single malfunction will not produce a hardover signal in more than one control axis. If the automatic pilot integrates signals from auxiliary controls or furnishes signals for operation of other equipment, positive interlocks and sequencing of engagement to prevent improper operation are required.

(g) There must be protection against adverse interaction of integrated components, resulting from a malfunction.

(h) If the automatic pilot system can be coupled to airborne navigation equipment, means must be provided to indicate to the flight crew the current mode of operation. Selector switch position is not acceptable as a means of indication.

Figure 56. 14 CFR 23.1329

6.5.2 Stall Barrier Certification Standards.

Artificial stall barrier systems provide some precedent for automatic intervention within an automatic pilot system. Stall barrier systems (stick pushers) are implemented on certain high-performance aircraft that cannot meet the stall requirements of 14 CFR 23.201 through aerodynamic design alone. These devices, covered under 14 CFR 23.691, are designed to

provide a pitch motion equivalent to that experienced during stalls of airplanes that naturally meet the stall requirements. Of particular significance is the fact that these artificial barrier devices are automatically activated when certain criteria are met and directly manipulate a flight control against the actions of the pilot. 14 CFR 23.691 identifies the usage of the autopilot pitch servo as one means to accomplish this action. Therefore, there is a regulatory precedent for an autopilot system providing some level of intervention. Interestingly, there is no TSO that covers artificial stall barrier systems, most likely because such equipment is always part of an initial type certificate. There is no known precedent for retrofit of stall barrier systems.

Figure 57 contains the text of 14 CFR 23.691. Again, a number of the principles of good engineering design practice are exemplified by these standards, but they do not explicitly apply to an envelope protection system that is supplementary in nature.

Sec 23.691 Artificial stall barrier system.

If the function of an artificial stall barrier, for example, stick pusher, is used to show compliance with §23.201(c), the system must comply with the following:

(a) With the system adjusted for operation, the plus and minus airspeeds at which downward pitching control will be provided must be established.

(b) Considering the plus and minus airspeed tolerances established by paragraph (a) of this section, an airspeed must be selected for the activation of the downward pitching control that provides a safe margin above any airspeed at which any unsatisfactory stall characteristics occur.

(c) In addition to the stall warning required §23.07, a warning that is clearly distinguishable to the pilot under all expected flight conditions without requiring the pilot's attention, must be provided for faults that would prevent the system from providing the required pitching motion.

(d) Each system must be designed so that the artificial stall barrier can be quickly and positively disengaged by the pilots to prevent unwanted downward pitching of the airplane by a quick release (emergency) control that meets the requirements of §23.1329(b).

(e) A preflight check of the complete system must be established and the procedure for this check made available in the Airplane Flight Manual (AFM). Preflight checks that are critical to the safety of the airplane must be included in the limitations section of the AFM.

(f) For those airplanes whose design includes an autopilot system:

(1) A quick release (emergency) control installed in accordance with §23.1329(b) may be used to meet the requirements of paragraph (d), of this section, and

(2) The pitch servo for that system may be used to provide the stall downward pitching motion.

Figure 57. 14 CFR 23.691

6.5.3 Stability Augmentation Systems Certification Standards.

14 CFR 23.691 contains no information with respect to expanding barrier protection (stall or otherwise) to other axes of flight or other performance parameters (e.g., overspeed). In this case, 14 CFR 23.672, “Stability Augmentation and Automatic and Power-Operated Systems,” might be consulted. Technically, 14 CFR 23.672 only applies when the system is required to meet the Part 23 stability requirements, but it still provides some regulatory insight about how such a system might be certified. In this case, the 14 CFR 21.16, “Special Condition,” issue paper may be required to explore the idea of this expansion.

Figure 58 contains the text of 14 CFR 23.672. Again, many principles of good engineering design practice are in evidence and could inform a negotiated standard for envelope protection systems certification, even though these standards do not directly apply to a system that, by its nature, is supplemental.

Sec 23.672 Stability augmentation and automatic and power-operated systems.

If the functioning of stability augmentation or other automatic or power-operated systems is necessary to show compliance with the flight characteristics requirements of this part, such systems must comply with §23.671 and the following:

(a) A warning, which is clearly distinguishable to the pilot under expected flight conditions without requiring the pilot's attention, must be provided for any failure in the stability augmentation system or in any other automatic or power-operated system that could result in an unsafe condition if the pilot was not aware of the failure. Warning systems must not activate the control system.

(b) The design of the stability augmentation system or of any other automatic or power-operated system must permit initial counteraction of failures without requiring exceptional pilot skill or strength, by either the deactivation of the system or a failed portion thereof, or by overriding the failure by movement of the flight controls in the normal sense.

(c) It must be shown that, after any single failure of the stability augmentation system or any other automatic or power-operated system—

(1) The airplane is safely controllable when the failure or malfunction occurs at any speed or altitude within the approved operating limitations that is critical for the type of failure being considered;

(2) The controllability and maneuverability requirements of this part are met within a practical operational flight envelope (for example, speed, altitude, normal acceleration, and airplane configuration) that is described in the Airplane Flight Manual (AFM); and

(3) The trim, stability, and stall characteristics are not impaired below a level needed to permit continued safe flight and landing.

Figure 58. 14 CFR 23.672

6.5.4 General Hardware and Software Certification Standards.

Since the instrument would contain both a microprocessor and software, it would have to be developed in accordance with the appropriate RTCA documents. In this case, DO-178B (level B) is appropriate for software, and DO-160E and DO-254 (if applicable) would be appropriate for the hardware.

7. THE GA ENVELOPE PROTECTION MARKET ANALYSIS.

This section provides a review of the light airplane market in the U.S. and the likely portion of the market that is addressable for envelope protection systems. The section concludes with an estimate of potential annual sales volume and revenue for envelope protection systems.

Data sources for this market overview were taken from 2006. Primary sources are the FAA GA Survey [20] and the GA Manufacturers Association International Shipment Report [5].

The U.S. GA fleet consists of fixed and rotary wing, propeller, and turbine-powered aircraft, gliders, and balloons. This market survey concentrated on fixed-wing, propeller-driven aircraft, the majority of which fall into the category of light aircraft.

7.1 U.S. PISTON-POWERED AIRPLANES.

The total number of piston-powered airplanes in the U.S. in 2006 was estimated at 214,188, of which 163,744 were active (flew at least 1 hour during the year). Of these, 145,036 are single-engine airplanes, and 18,708 are twin-engine airplanes.

Figure 59 shows the active piston-powered fleet distributed by age. Of the 163,744 active piston-powered airplanes, 90% are over 20 years old. The majority of them, 68%, were built in the 25 years from 1962 through 1986. Only about 2% of the active population was built during the decade from 1987 through 1996. About 8% of the population is new, having been built during the 10 years from 1997 through 2006. The remaining 22% of active piston-powered airplanes are over 45 years old.

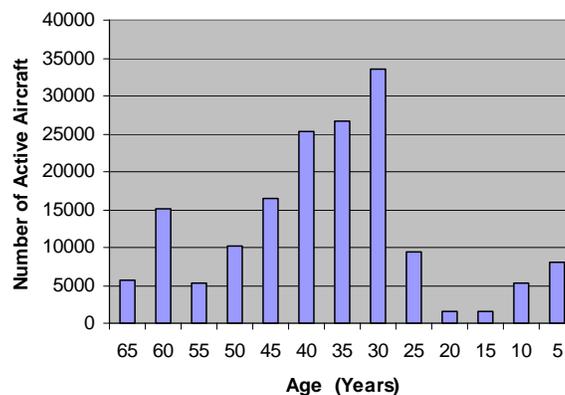


Figure 59. Active Piston-Powered Airplanes in U.S., Distributed by Age

The year 2006 was a good year for U.S. manufacturers of light airplanes, representing a peak production year for the decade. In this year, 2287 piston-powered airplanes were delivered worldwide by U.S. manufacturers. The average for the decade from 1999 through 2008 was 1863 aircraft¹. It is interesting to note that an average year's worldwide shipment from U.S. manufacturers represents only 1.1% of the current active population of aircraft within the U.S.

This suggests that, in terms of numbers of potential aircraft for application of envelope protection, the retrofit market will remain much larger than the forward-fit market, at least until the large population of aircraft manufactured between 25 and 45 years ago becomes uneconomical to continue operating. Figure 60 shows the percentage of the piston-powered airplane population in the U.S. that is active as a function of aircraft age. From this “survival curve,” it appears that even 50 years after production, 2/3 of the aircraft produced remain in active service. If this remains true into the future, it would imply that the retrofit market for aircraft manufactured in the late 1960s to early 1980s will remain viable at least until the early 2030s, or another 20 to 25 years from the writing of this report.

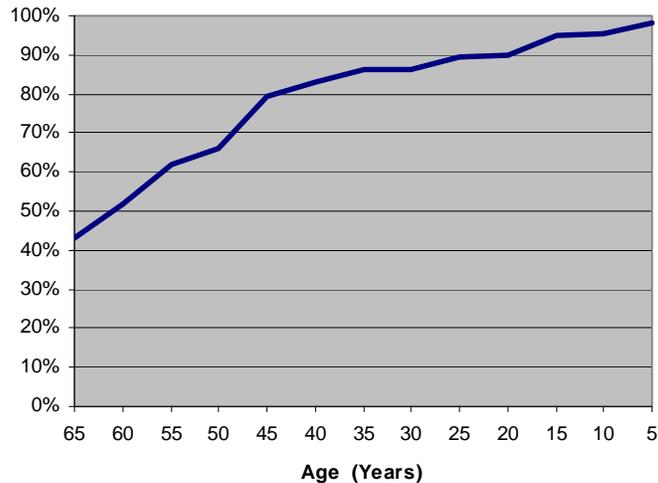


Figure 60. Percentage of Piston-Powered Aircraft Remaining Active as a Function of Age

7.2 PISTON-POWERED U.S. FLEET CHARACTERIZED BY INSTALLED AVIONICS.

For the purpose of evaluating market segments of the U.S. retrofit market for avionics, it is instructive to consider the types of avionics currently installed in the fleet. Table 4 separates the fleet according to the following equipage considerations.

¹ By comparison, in 1978, the peak production year for GA, there were 17,817 GA aircraft produced. This number represents all types, including jets. However, the great majority were piston-powered aircraft [21].

Table 4. Active Piston-Powered U.S. Aircraft Characterized by Installed Avionics

Avionics Installed	Single Engine		Twin Engine		Total Piston Aircraft	
	Number	%	Number	%	Number	%
Electrical system	133,018	91.7	18,374	98.2	151,392	92.5
Localizer	90,689	62.5	18,116	96.8	108,805	66.4
Wing leveler	51,511	35.5	12,782	68.3	64,293	39.3
Altitude hold	35,740	24.6	14,634	78.2	50,373	30.8
Approach mode	24,715	17.0	12,697	67.9	37,412	22.8
Altitude preselect	11,191	7.7	3,530	18.9	14,720	9.0

First, consider that a fraction of the active piston-powered fleet has no electrical system. This is about 7.5% of the active piston-powered airplanes in the U.S., leaving only 151,392 airplanes with electrical systems installed.

To be a candidate for retrofit of any advanced avionics, a certain minimum level of instrumentation for instrument flight (the presence of a localizer) suggests a class of airplane with sufficient value to support further investment. Approximately two-thirds of the active fleet meets this criterion, or 108,805 airplanes.

Since active envelope protection systems would likely provide some functions overlapping those of current autopilots, it is instructive to further characterize the fleet according to types of autopilot functions already available. For the increasingly sophisticated functionalities of (1) wing leveler, (2) altitude hold, (3) approach mode, and (4) altitude preselect, the percentages of the active piston-powered fleet with such capabilities are 39.3%, 30.8%, 22.8%, and 9.0%, respectively. Wing levelers are present in 64,293 aircraft, while altitude preselect is present only in 14,720 aircraft.

7.3 ENVELOPE PROTECTION RETROFIT MARKET SEGMENTS.

The addressable retrofit market for the Basic Advisory System and for the Active Envelope Protection System can be segmented as follows.

The Basic Advisory System is an advisory-only system with no flight control functionality. The total potentially addressable market for such a system would be the entire population of aircraft with electrical systems installed. (Estimates of future market penetration for each product offering are discussed in section 7.5.)

For an Active Envelope Protection System, the market offering will be an autopilot that has, in addition to typical autopilot features, some envelope protection features built in as well. The total addressable market for such an offering will consist of customers who would consider the purchase and installation of a new autopilot. These aircraft owners will be in the market for one of the following three reasons: (1) they desire a first autopilot for their airplane; (2) they wish to

upgrade an existing autopilot; or (3) their current autopilot is broken, and they would like to replace it.

The overall size of each of these potentially addressable market segments can be calculated from the numbers shown in table 4. The resulting market segment descriptions and sizes are shown in table 5.

Table 5. Envelope Protection Addressable Market Segment Estimates

Market Segment	Segment Description	Calculation	Size
Advisory system only	All active piston aircraft with electrical systems.	NA	151,392
First autopilot installation	Active piston aircraft with localizer but without wing leveler.	108,805-64,293	44,512
Upgrade to basic autopilot	Active piston aircraft with wing leveler but without altitude hold.	64,293-50,373	13,920
Upgrade to capable autopilot	Active piston aircraft with altitude hold but without approach mode.	50,373-37,412	12,961
Autopilot replacement	Active piston aircraft with approach mode.	NA	37,412

7.4 RETROFIT MARKET PENETRATION AND ANNUAL SALES VOLUME ESTIMATES.

Annual sales volume can be estimated by assuming the degree of market penetration likely for each of the addressable market segments, and by assuming the length of time it would take to achieve that ultimate market penetration (i.e., to achieve market saturation). In the panel-mount avionics retrofit market, 15 years is a typical product life cycle, i.e., 95% or more of the market penetration will be fulfilled within a period of 15 years, for a given new avionics product². While sales volume typically is maximum during the first 5 to 8 years of the product's initial offering and gradually diminishes thereafter, for simplicity a constant annual sales volume of the life cycle was assumed. Table 6 shows the assumed market penetrations, and the resultant retrofit annual sales volumes, for the market segments already identified.

²The product life cycle is significantly shorter for noninstalled, hand-held avionics.

Table 6. Envelope Protection Market Segment Estimated Annual Sales Volumes

Market Segment	Segment Size	Assumed Market Penetration (%)	Annual Volume as Percentage of Segment (15-Year Life Cycle) (%)	Annual Sales Volume Estimate
Advisory system only	151,392	5	0.3	454
First autopilot installation	44,512	20	1.3	578
Upgrade to basic autopilot	13,920	30	2.0	278
Upgrade to capable autopilot	12,961	20	1.3	168
Autopilot replacement	37,412	30	2.0	748
Autopilots Total				1772

7.5 FORWARD-FIT MARKET.

The preceding market size and sales volume estimates accounts only for the retrofit market. While this is sizable, the forward-fit market also is a potential addressable market for envelope protection.

For the sake of envelope protection revenue estimates, it was assumed that the average production rate for new piston-powered aircraft that has occurred over the past decade is sustained (1863 aircraft per year, on average).

It must also be assumed that some fraction of those aircraft could potentially incorporate envelope protection features. Since the majority of new-production certified piston-powered aircraft include an autopilot, a potentially addressable forward-fit market equal to 80% of new-production annual volume, or 1490 aircraft was assumed. It was also assumed that 50% of the addressable market eventually will include basic envelope protection features.

The above assumptions indicate there would be a potential for forward-fit envelope protection features in up to 745 new-production aircraft.

7.6 ANNUAL PRODUCT REVENUE ESTIMATE.

To estimate total product revenue for envelope protection systems, average retail selling prices for these systems must be assumed. Currently, retail sale prices of the most popular autopilots for certified aircraft range from \$9,600 for a very basic, rate-based system to \$25,000 for a

full-featured, attitude-based system.³ Without regard for the likely range of options that would be offered in autopilot systems with envelope protection, an average retail sale price of \$18,000 was assumed for all autopilots with envelope protection included.

Advisory-only systems for envelope protection are likely to result in sales only if priced competitively with replacements for existing stall warning systems. Therefore, a practical upper limit on advisory-only systems would be a retail price of \$1200.

For forward-fit sales, revenue estimation required some difficult pricing assumptions. Forward-fit sales are generally based upon full-package prices with only a few major options offered. In general, the prices of individual features within a given subsystem are not quoted separately. Therefore, a somewhat arbitrary value must be assigned to envelope protection features within an autopilot system. For the purpose of forward-fit revenue estimation, an arbitrary value of \$2500 was assigned for envelope protection features within an autopilot.

Given these assumptions, the total annual revenue from the sale of envelope protection systems can be estimated as shown in table 7.

Table 7. Envelope Protection Systems Annual Sales Revenue Estimate

Sales Type	Annual Sales Volume	Average Retail Price	Annual Revenue
Retrofit advisory system only	454	\$1,200	\$544,800
Retrofit autopilots with envelope protection	1772	\$18,000	\$31,896,000
Forward-fit envelope protection feature	745	\$2,500	\$1,862,500
Total			\$34,303,300

The total retail market size for envelope protection systems in piston-powered aircraft in the U.S. is estimated by the foregoing as about \$34.3 million annually.

It should be understood that market share for any particular individual company, if successful, would likely range from 10% to 70% of the total annual market. In addition, prices charged by avionics manufacturers to their distributors are typically about 60% of the retail price of the product. Given a 50% market share, a successful manufacturer could, therefore, expect revenues from a suite of envelope protection or autopilot products on the order of \$10 million annually.

7.7 INDEPENDENT VALIDATION OF MARKET ESTIMATES.

A number of significant assumptions were made to arrive at the foregoing market size estimates, including market saturation percentages and average retail sales prices. As a means of

³One full-featured system is offered at \$44,570 for retrofit, but has virtually no sales as a result.

independently validating the conclusions reached, the example of S-TEC, a dominant manufacturer of retrofit autopilots for the past 3 decades in the U.S., was used. S-TEC's competitors in the certified marketplace have included Century and, to a lesser extent, King and, more recently, Chelton. However, S-TEC autopilots are by far the most commonly encountered retrofit autopilots in the GA fleet.

Detailed information on S-TEC's business is proprietary in nature and, therefore, difficult to obtain. S-TEC was recently been acquired by Cobham Group, a United Kingdom conglomerate, making access to detailed information about S-TEC itself as an independent entity even more difficult. However, the following facts were obtainable.

In the "Cobham Update," dated December 2007 [22], the acquisition of S-TEC is discussed, and the following information is given:

"It was announced in November that S-TEC will be acquired by Cobham, bringing shares of the general aviation retrofit and OEM markets. Based in Mineral Wells, Texas, the company was founded in 1978 and has 180 employees and 485 dealers worldwide. They have delivered over 38,000 autopilot systems and currently hold OEM positions on the market leading Cirrus SR22 and Eclipse 500 aircraft."

The delivery of 38,000 autopilots over a period of 30 years implies an average annual sales volume of 1,267 units. This number compares favorably to the total market annual estimate of 1,772 autopilots from table 6. If this annual estimate of retrofit autopilot sales applied over the first 30 years of S-TEC's history, it would suggest a 70% market share for S-TEC, which would be consistent with its status as a dominant provider of retrofit systems for GA.

7.8 ACCIDENT PREVENTION ECONOMIC IMPACT OF GA ENVELOPE PROTECTION.

It is important to note that the economic impact of the sale of envelope protection systems is not simply the retail value of the systems sold. A much larger economic savings is realized by the value of the accident prevention afforded by the installed systems.

Among single-engine, fixed-gear aircraft, four accident categories are responsible for 75% of fatal accidents: maneuvering flight (34%), weather-related (14%), takeoff/climb (15%), and descent/approach (13%) [3]. Approximately half of these accidents are due to aircraft loss of control and could have been potentially prevented by installing an envelope protection system.

Using the market penetration assumptions shown in table 6, approximately 23% of the overall active piston-engine aircraft fleet would eventually be equipped with some form of envelope protection⁴. In 2006, there were 273 fatal fixed-wing aircraft accidents in the U.S., resulting in 488 fatalities [3]. If 23% of those accidents involved aircraft with installed envelope protection

⁴Most likely, the equipped aircraft would be those that are most active; however, whether the most active aircraft are those most likely to be involved in a loss-of-control accident or not is debatable.

systems and half of those were prevented, 31 accidents would have been prevented and about 55 lives would have been saved each year. Assigning an economic value of \$6.0 million to each life saved, and ignoring other damages, the economic benefit of accidents prevented each year is \$330 million, about ten times the annual revenue from sales of the envelope protection systems themselves.

8. CONCLUSIONS.

The work performed during the first year of this project demonstrated that Basic Envelope Protection for general aviation (GA) aircraft is both technically and economically feasible. While the idea of envelope protection for light aircraft is not new, none have been fielded in a commercial product. Previous systems, while effective, were complex, lacked a clear roadmap to certification, and were economically prohibitive to implement. This effort focused on much simpler systems that have a clear path to a marketable product.

A spectrum of solutions for envelope protection has potential for affordable retrofit into the existing light aircraft fleet, as well as application to the forward-fit market.

At the very low-cost end of the spectrum, a Basic Advisory System can provide visual and auditory warnings of impending stall and stall-spin, over-g, and overspeed flight conditions for about the same price as a replacement stall warning system alone. The Basic Advisory System can alert the pilot to these dangerous impending situations with sufficient advance warning to allow manual control intervention before aircraft controllability is compromised.

Mid-range solutions are possible that could provide single- or dual-axis envelope protection as add-on features to existing autopilots, with appropriate visual and auditory annunciations to inform the pilot that an envelope protection feature has been activated. Most of these features can be made available as added capability within either rate- or attitude-based autopilots. The most advanced capabilities and best performance are likely to require the use of digital attitude and angular rate data from an Attitude and Heading Reference System. While the retrofit market currently does not have a certified digital attitude-based autopilot, this situation will almost certainly change in the near future, enabling the provision of envelope protection features to some of the existing fleet as autopilots are upgraded or replaced.

Force Gradient Control is a newly conceived form of aircraft control that allows simultaneous pilot/autopilot control of cable-controlled aircraft on a continuous basis without interfering with manual flight operations. Force Gradient Control requires development of a new, advanced type of servo that is back-drivable and designed to provide controlled levels of output torque to the cable control system of the aircraft. This type of servo will enable full-time stability augmentation and envelope protection features to be provided to both retrofit and forward-fit aircraft by an advanced digital autopilot system in a cost-effective manner.

To determine certification basis, the Code of Federal Regulations (CFR), existing Technical Standard Orders (TSO), and Advisory Circulars (AC) have been consulted. The certification basis for autopilots is defined by 14 CFR 23.1329 and TSO-C9c. With respect to envelope protection, there is a precedent for limited systems in light aircraft. All aircraft certificated under

14 CFR Part 23 must have a stall warning (14 CFR 23.207), which is an advisory-only type of envelope protection. Of even greater significance are stall barrier systems (stick pushers), which are implemented under 14 CFR 23.691. The certification basis of stall warning and stick pusher systems is used as a basis for full envelope protection systems.

A market analysis was conducted to determine the market size for envelope protection systems. Envelope protection systems are likely to have much more appeal if they are incidental features to other systems that have more perceived utility. Active envelope protection systems will likely need to be embedded in highly capable autopilot systems that provide significant perceived benefits during normal aircraft operations for pilot/owners to be willing to invest in their purchase and installation. Within the U.S., there appears to be a potential annual market of 1700 units at an average retail sale price of \$18,000.00 for sophisticated autopilots. Basic advisory-only systems represent an estimated annual market of 450 units at a retail sale price of \$1200 each. The estimated sales of systems of all types with envelope protection features are \$34 million. Given the estimated mature market penetration of GA envelope protection systems, a savings of \$165 million annually would result from accidents prevented by these systems.

Developing inexpensive envelope protection systems is an ambitious task and the effort has only begun to fully develop the concepts presented herein. Envelope protection involving active manipulation of flight control raises a number of practical considerations involving human factors and certification. In particular, Force Gradient Control, while innovative, raises many issues regarding pilot-controller interaction and pilot acceptance. To address these issues in a rigorous manner, a cockpit simulator for a light aircraft will be constructed, paying particular attention to accurate modeling of stick force gradients, so that the pilot-controller implications of force gradient control can be studied in depth. In parallel, prototype force gradient servo hardware will be developed. The final phase of the research will involve flight testing a prototype system on a single-engine, light aircraft.

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