



Assessment of the State of the Art of Flight Control Technologies as Applicable to Adverse Conditions

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Summary

A survey of literature from academia, industry, and other Government agencies was reviewed to assess the state of the art in flight control technologies as related to the identified adverse conditions. A general state of the art in adaptive flight control is summarized first, followed by an assessment of the state of the art as applicable to 13 identified adverse conditions. The state-of-the-art summaries include technologies not specifically related to flight control, but may serve as inputs to a future flight control algorithm.

The adverse conditions were determined as a result of a previous study and can be found in NASA Technical Memorandum entitled “Causal Factors and Adverse Conditions of Aviation Accidents and Incidents Related to Integrated Resilient Aircraft Control.” The types of adverse conditions are divided into three separate groups: failure of aircraft system or component, damage to a structure or component, and control upsets related to pilot error or another cause that cannot be regulated by aircraft technology.

In general, there were two distinct methods for implementing adaptive flight control systems. In the first method, the system assists the pilot in operating the aircraft in a degraded state by providing additional information on the degradation state of the aircraft and then makes calculations relating to alternative use of controls or alternative maneuvers. The second type of implementation involves no change in the pilot’s method of operation in relation to a nominal operating environment. The adaptive control system takes the nominal control inputs given by the pilot, performs calculations based on the degradation state of the aircraft, and sends alternative commands to the vehicle control surfaces and/or propulsion system. This method is very different than the first, as the pilot is not required to alter the operation of the plane due to the degradation.

Much more research is being done on failures and degradation of specific components in relation to adaptive control systems. Although component research is important, as it can provide better input data into adaptive control systems, more can be done to advance the state of the art of the actual adaptive control systems. In regards to the two methods of implementing adaptive control, the trend is that the state of the art is moving in the direction of systems in which the pilot operates the aircraft the same in both nominal and off-nominal conditions where the adaptive control system itself alters the commands that go to the control surfaces and propulsion system when operating in an off-nominal state.

1.0 Introduction

The study reported here has been completed for the Integrated Resilient Aircraft Control (IRAC) Project (Ref. 1), which is a part of the National Aeronautics and Space Administration's (NASA's) Aviation Safety Program (AvSAFE). Specifically, this study addresses the assessment of the state of the art of flight control systems and/or technologies as applicable to adverse conditions. The adverse conditions were determined as a result of a previous study and can be found in NASA Technical Memorandum entitled "Causal Factors and Adverse Conditions of Aviation Accidents and Incidents Related to Integrated Resilient Aircraft Control" (Ref. 2).

Table 1 summarizes the results of an examination of statistical and prognostic data to interpret and extract information about accidents and incidents caused by loss of control. The table includes potential adverse conditions against which flight, propulsion, and mission-adaptive control approaches can be evaluated. In this analysis, publicly available accident and incident data from the National Transportation Safety Board (NTSB), Federal Aviation Administration (FAA), and Aviation Safety Reporting System (ASRS) were examined, and 13 categories of adverse condition subtypes are documented. All of these data sources can be accessed using the Aviation Safety Information Analysis and Sharing (ASIAS) System (Ref. 3). The types of adverse conditions are divided into three separate groups: failure of aircraft system or component, damage to a structure or component, and control upsets related to pilot error or another cause that cannot be regulated by aircraft technology.

The study reported here is based on research related to flight control systems and technology in general, as well as specific information related to each of the 13 subtype categories of adverse conditions. Included is a summary of the results of a survey of literature from academia, industry, and other Government agencies to assess the state of the art in flight control technologies as related to the identified adverse conditions. First, the state of the art in adaptive flight control is summarized. Next, the state of the art in flight control technology is discussed in regards to each category of adverse conditions. These summaries may include state-of-the-art technologies not specifically related to flight control that may serve as inputs to a future flight control algorithm, such as advanced sensor data. These discussions are meant to serve as a summary of the technologies. An indepth discussion of each technology mentioned would not be feasible in a report of this breadth. The references given provide more detailed information. Additional references not cited in the paper that may offer a broader perspective of the current technologies are available by contacting the author.

2.0 Establishing Adverse Conditions Related to Aviation Safety

NASA conducted an analysis to document the results of an examination of statistical and prognostic data to interpret and extract information about the causes of loss-of-control accidents and incidents. In this analysis, publicly available accident and incident data from the NTSB, FAA, and ASRS were examined.

2.1 Causal Factor Analyses of National Transportation Safety Board, Federal Aviation Administration, and Aviation Safety Reporting System Accident and Incident Data

The analysis was conducted to determine the causal factors of accidents and incidents associated with loss of control of commercial aircraft during 1988 to 2003. In this analysis, "commercial" is defined as Part 121, Scheduled Part 135, and Nonscheduled Part 135 flights. Part 121 operations applies to major airlines and cargo carriers that fly large transport-category aircraft, while Part 135 applies to commercial aircraft air carriers commonly referred to as commuter airlines. Prior to March 1997, Part 121 operations included aircraft with 30 or more seats. In March 1997, the definition of Part 121 operations changed and now includes those aircraft with 10 or more seats. Scheduled operation refers to "any common carriage passenger-carrying operation for compensation or hire conducted by an air carrier or commercial operator for which the certificate holder or its representative offers in advance the departure location, departure time, and arrival location." A nonscheduled operation refers to "any operation for compensation or hire in

which the departure time, departure location, and arrival location are specifically negotiated with the customer” (Ref. 4). The safety risks of both accidents and incidents are defined as follows (Ref. 5):

Accident an occurrence associated with the operation of an aircraft, which takes place between the time any person boards the aircraft with the intention of flight and all such persons have disembarked, and in which any person suffers death or serious injury, or in which the aircraft receives substantial damage

Incident an occurrence other than an accident, associated with the operation of an aircraft, which affects or could affect the safety of operations

The source for accident data is the NTSB Aviation Accident and Incident Data System, while the source for incident data is the ASRS Incident Data System.

For each accident and incident, the cause of the loss of control was determined. In some cases, multiple causal factors were cited for accidents or incidents. The data is summarized in a table that is explained in the next section.

2.2 Adverse Conditions Table

The purpose of the adverse conditions table is to provide focus to the technology validation strategy. These adverse conditions are categorized into three types: failure, damage, and upset. Failure is defined as a system or component that does not work properly including degradation of performance. Damage is defined as a structure or component that is broken, and upset consists of pilot error and/or loss of control due to occurrences that cannot be regulated via aircraft technology.

The initial adverse conditions table found in the IRAC Technical Plan was updated by collecting accident and incident data gleaned from findings within the ASRS and NTSB databases. The intent was to call attention to damage conditions that occur frequently while providing insight on their severity and frequency (Ref. 2).

Thirteen adverse conditions subtypes of significance were found. Suggested initial test conditions are provided in the table for each of the adverse condition subtypes. The severity and frequency of each subtype is provided also as a means of prioritizing the example damage conditions. Finally, applicable IRAC milestones are referenced. Table 1 is the updated adverse conditions table.

TABLE 1.—INTEGRATED RESILIENT AIRCRAFT CONTROL ADVERSE CONDITIONS

Adverse condition	Adverse condition subtype	Severity (frequency)
Failure: System/component does not work properly. Includes degradation of performance.	1. Landing gear <ul style="list-style-type: none"> • Nose wheel steering (NWS) • Main gear and tire • Anti-skid/braking system • Gear extend/retract mechanism 	Accident (1) Incident (597)
	2. Avionics <ul style="list-style-type: none"> • Instrumentation/communication/navigation <ul style="list-style-type: none"> – Flight management/monitoring system – Weather radar 	Accident (1) Incident (347)
	3. Electrical <ul style="list-style-type: none"> • Auxiliary power unit • Radar • Actuator wire breaks • Wire chafing 	Accident (3) Incident (25)

TABLE 1.—Concluded.

	4. Hydraulics	Accident (0) Incident (24)
	5. Static and dynamic actuator failure effects (single actuator and multiple actuator failures)	Accident (n/a) Incident (n/a)
	6. Environmental control system <ul style="list-style-type: none"> • Pressurization system 	Accident (1) Incident (9)
Damage: Structure/component is broken	1. Propulsion system <ul style="list-style-type: none"> • Throttle and/or power-level system • Engine <ul style="list-style-type: none"> – Engine icing – Fire • Fuel system • Vacuum pump 	Accident (20) Incident (182)
	2. Control surfaces <ul style="list-style-type: none"> • Rudder, aileron, or elevator 	Accident (8) Incident (144)
	3. Aerodynamic and structural damage (wing and/or tail)	Accident (1) Incident (41)
Upsets: Consists of pilot error and/or loss of control due to occurrences that cannot be regulated via aircraft technology	1. Electrical	Accident (3) Incident (25)
	2. Severe weather <ul style="list-style-type: none"> • Icing • Winds • Poor evaluation of weather 	Accident (56) Incident (n/a)
	3. Inadequate attitude/airspeed, and/or stall/spin	Accident (36) Incident (n/a)
	4. Pilot <ul style="list-style-type: none"> • Improper use of controls • Inadequate training or experience 	Accident (104) Incident (n/a)

3.0 General Assessment of State of the Art of Flight Control

This section includes a general overview of the current state of the art in adaptive flight control. The objective of this study is to provide an assessment of the state of the art as applicable to the adverse conditions identified in Table 1. Unfortunately, flight control technology is often not specific to a certain adverse condition. In the following section, research presented is specific to the adverse events but not necessarily specific to flight control. The reason for including this information is that there are many areas where state-of-the-art research in sensors or predictive algorithms may be very useful as inputs to adaptive control schemes that have yet to be designed. In addition to being a survey of the current state of the art, this study will hopefully spur new ideas on adaptive flight control.

3.1 Compensating for Damage and/or Reduced Performance

One such use for this technology is as an adaptive flight controller that takes as input, information on damage or reduced utility of actuators and control surfaces, and calculates compensatory states for all working components (Ref. 6). A second example uses damage or reduced utility inputs and uses them to calculate a revised flight envelope to be used by the pilot (Ref. 7). A specific example of an adaptive flight controller with a neural network is a system installed on the NASA Dryden NF-15B Intelligent Flight Control System (IFCS) aircraft. Its adaptive flight controller is equipped with a neural network to simulate the effects of a locked stabilator. With one stabilator locked, a conventional command given by the pilot would result in a response that is different than expected. For example, a simple pitch command would not only cause reduced pitching movement because one stabilator is not working, but it would also cause a slight roll due to the asymmetry. The system was a direct adaptive system and was driven by feedback errors making prior knowledge of the failures unnecessary. The simulator was flown with three

different scenarios. The first scenario was a control case that had no failure. The second had a locked stabilator with no adaptive control, and the third had the locked stabilator with the adaptive control algorithm. A pitch maneuver was attempted, and the simulator logged both the pitch and roll response of the aircraft. The adaptive control did improve pitch response, but roll was still induced (Ref. 8).

Another variant of adaptive flight control translates pilot control input into the proper throttle and control surface inputs while compensating for any damage conditions that may exist. One such system is called an EZ-Fly system (Ref. 9), which utilizes an artificial neural network. The system responds differently to stick and throttle commands than that of a normal aircraft. For example, the longitudinal movement of the stick commands the plane to a set flight path angle instead of a pitch angle, and the equivalent occurs with lateral movement. Thus, the pilot is not controlling the actual control surfaces but rather setting the angles at which he wants the plane to fly and letting the flight controller use the control surfaces accordingly. This lets the flight controller compensate for damage to control surfaces or actuators without any change in behavior from the pilot. In addition, the throttle is replaced with a speed lever, and the flight controller calculates the appropriate throttle positions. Simulator tests show that this system significantly increased the amount of occurrences where pilots kept control of the airplane when damage conditions were present as compared to conventional controls. This was especially true for inexperienced pilots that did not have as much training in regards to controlling a plane when not all the control surfaces are available (Ref. 9).

3.2 Retrofit Upgrades

Retrofit software upgrades to flight controllers of production aircraft exist that allow for fault-tolerant calculations to be made. For example, a structure learning modeling algorithm, which is a type of neural network, has been designed to retrofit an F/A-18 aircraft. The algorithm comes into play when faults in control surface or actuators, adverse weather, icing conditions, or other conditions are present, which cause the aircraft dynamics to differ from normal operations. The algorithm calculates corrections that will be applied to control inputs and attempts to return controls to a normal state. This was tested using both Boeing and Air Force pilots in simulated F/A-18 maneuvers (Refs. 10 and 11).

3.3 Flight Control Through Engine Response

In addition to calculating compensatory trims for a decreased set of available control surfaces, there has also been research into using variable engine response, adding another element to the available methods of control (Ref. 12). In some extreme cases, this method might even be one of the only options left for controlling an aircraft. Researchers at NASA Glenn Research Center and N&R Engineering have created a simplified dynamic model of a 40,000-lb thrust turbofan engine using a MATLAB/Simulink-based linear model. Under various airframe damage scenarios, the model determines an appropriate thrust response (Ref. 13).

3.4 Test and Validation of New Adaptive Controllers

Once new adaptive flight controllers are designed, test and validation become very important to the development process. Unless they are shown to increase safety, manufacturers will not want to include these new systems on new aircraft, and operators will not want to retrofit existing ones. As flight tests are extremely expensive, other methods of testing have been developed. Researchers at NASA Langley Research Center have developed the Airborne Subscale Transport Aircraft Research (AirSTAR) system, which is a collection of dynamic subscale models of various aircraft operated out of a control center. Damage conditions can be replicated in realtime, control algorithms can be loaded onto the system, and pilots can test adaptive control systems in a live setting (Ref. 14). The Massachusetts Institute of Technology has also developed an indoor facility for testing flight control technology on highly aerobatic unmanned aerial vehicles (UAVs). This facility is called the Real-Time Indoor Autonomous Vehicle Test

Environment (RAVEN) (Ref. 15). The use of UAVs allows for flight control technologies to be tested in a real-time setting that is much less expensive than full-scale flight tests (Ref. 16).

In addition to UAV testing, another less expensive option is through the use of flight simulators. One example of an extensive study utilizing simulators was conducted by a group of researchers in the Netherlands. The researchers reconstructed a 1992 accident that occurred in Amsterdam on a simulator, and had a number of pilots recreate the scenario with various fault-tolerant adaptive control strategies available. The researchers conducted the scenarios with both manual control from the pilots and automatic control. In both cases it was very clear that catastrophic events can be potentially avoided through the use of these automated flight control algorithms. The pilots noted that in most cases the control of the aircraft was very comparable before and after the failure. The study also asked pilots what was most important for future improvements. It was noted that the determination, presentation, and possibly the protection of the safe flight envelope could be improved upon (Ref. 17).

The next section goes into more detail in relation to each of the adverse conditions cited in Table 1. Because many of the possible adverse conditions in the table do not have specific flight controllers designed for them, the summaries also include state-of-the-art detection technologies, predictive algorithms, or other information that might be useful for input into a new adaptive flight control algorithm.

4.0 Flight Control Systems and Technologies in Relation to Specific Adverse Conditions

This section contains the results of the literature survey conducted to document the state of the art in flight control systems and technologies as applicable to the 13 adverse conditions listed in Table 1. The findings for each adverse condition are summarized below.

4.1 Adverse Conditions Involving Failure of an Aircraft System or Component

4.1.1 Landing Gear

Although faults in the landing gear and braking systems do not cause loss of control in the air, they are responsible for a significant number of accidents and incidents on the ground. If faults are known in advance, it might be possible to design a flight control system that could inform the pilot to alter his landing technique to decrease the risk of losing control of the aircraft upon landing. The current methods used by commercial airlines in regards to monitoring the health of landing gear mostly relate to routine maintenance and visual inspections. Additional maintenance may also be performed based on flight data or pilot observations. For example, a perceived hard landing by the pilot might warrant some extra maintenance procedures. The problem with this method is that some operational scenarios that put larger than normal loads on the landing gear may not be reported if the pilot does not think of the scenario as a hard landing. Research is being conducted to design a load sensor to be able to monitor this information (Ref. 18). Currently, structural sensors are not integrated into any landing gear systems. Even if a scenario causes some sort of damage to the structure, and it does get reported, it is possible that a visual inspection will not find the problem. For example, some stress fractures to the structure may not be visible without disassembling the main gear. A technique called acoustic emission is being developed that could detect faults in structures, breakage of seals, or other problems. During inspection, the technician uses a device to propagate acoustic waves, and sensors pick up potential variations in the waves caused by faults (Ref. 19). Another problem that occurs in landing gear is shimmy during taxiing and landing. Shimmy is an oscillation of the structure that is normally caused by rough runways and is usually around 10 to 30 Hz (Ref. 20). Although shimmy does not usually cause catastrophic failures, it can cause excessive wear over time. Current methods for dealing with shimmy include physical dampers, but this cannot adapt to changing situations. A new adaptive model under development uses sensors to detect shimmy, and then

calculates the taxiing velocity and yaw angle to minimize the shimmy, and gives this information to the pilot (Ref. 21). Currently, no production aircraft have this technology.

Conventional anti-skid systems consist of sensors that are used to detect when wheels are locked, and the brakes are pulsed accordingly. Better algorithms in the anti-skid system control unit could help decrease skids and stopping distance and increase reliability. There are a number of researchers working on developing these algorithms for use in anti-skid controllers (Ref. 22). There are also units that are designed to detect potential faults in the braking system. By utilizing braking data, an anti-skid control unit produced by General Atomics has the capability to detect anomalies in actual braking performance in contrast to expected performance. These anomalies act as a red flag for potential faults in the system (Ref. 23). Although this helps detect potential failures as they occur, there is not much on the market to detect early stages of failure. The products on the market, such as the controller from General Atomics, are backward looking and the mitigation is based on maintenance. Some research is being conducted in regards to a brake monitoring system that will offer some prognostic capabilities. This system involves using sensors to monitor wear on friction surfaces and pressure sensors to monitor conditions in hydraulics. As anomalies from normal sensor data become apparent, the system reports to a user interface that the risk of failure is high for a specific component (Ref. 24). Although this technology does not include fault mitigation, it can help increase operator awareness of conditions and decrease costs by reducing the need for frequent routine maintenance.

4.1.2 Avionics

One way that faults in instrumentation and navigation equipment can indirectly cause a pilot to lose control of an aircraft is if the pilot does not know that the equipment is faulty. If they lack this knowledge, and continue to rely on the equipment, they may have an incorrect perception of their current flight conditions and perform a maneuver that causes them to lose control. Another common problem related to faults in instrumentation, communication, and navigation is that faults are often noticed by the flight crew, but detection systems report that “no fault is found” (Ref. 25). An intelligent flight control system that was aware of these faults could report them to the flight crew, hopefully preventing potential accidents or incidents. Current methods of detection are similar to those of wiring chafing (which is discussed in the next section), in which impedance is measured for various electronics, and variations from the norm are detected as faults. The problem is that many times the variation in impedance is too small to be detected. One method that is promising in regards to finding these faults is called pulse-arrested spark discharge (PASD), which can be used to detect faults in electronics that cannot be detected using impedance methods (Ref. 26). In particular to navigation, the increased use of Global Positioning Systems (GPSs) has made faults in onboard navigation equipment much less relevant, as it uses data transmitted via satellites as opposed to electronics integrated with the rest of the aircraft. Along these same lines, utilization of wireless networks onboard could reduce the reliance on physical wiring in the future, which would eliminate many of the current failure modes (Ref. 27). Technologies related to weather systems in particular will be discussed later in this report.

4.1.3 Electrical

Over time, the insulation in wires that are near structures or moving parts can be degraded by friction. If the insulation is entirely rubbed off, it is possible for the wire to cause a short in the electrical systems. If these faults (or risk of fault) were able to be detected, an adaptive control system might be able to be designed to selectively isolate these areas from the rest of the system to protect electrical equipment from shorts. The most common technique to detect wire chafing in current aircraft is through visual inspection. This problem occurs increasingly as aircraft fleets age, and 43 percent of electrical system mishaps are related to connectors and wiring (Ref. 28). As we move towards more electric aircraft, the increased amount of wiring will only make this problem more important. Wire placement is a big driver of these problems, as wire bundles closer to hydraulics or airframe structures are more prone to chafing. One simple method of mitigation is to use standoff clamps to hold wire bundles away from these structures

(Ref. 29). Some more advanced methods of detection use differences in impedance to detect flaws in insulation before the conductor inside is harmed and shorts occur. However, one drawback to this method is that it does not help locate the area of the problem on the wire (Ref. 30). A company called Innovative Dynamics planned an integrated test of a wire chafing sensor in a Goodrich wiring harness. As the sensor becomes chafed, it should make maintenance technicians aware of the problem before the actual wires are harmed (Ref. 31).

Another detection method that is especially promising because it can be used to both detect and locate faults in a wire harness is PASD. This method can find faults that would only produce undetectable changes in impedance and can be used for multiple other purposes in addition to detection of wire chafing (Ref. 32). Another new type of sensing technology involves wrapping fiber optic cables around a wire bundle. As the fiber becomes chafed or breaks, the decreased transmission or short is easily detectable, as well as the location on the wire bundle (Ref. 33). As electric aircraft technology advances, wireless networks may be able to eliminate a lot of these problems (Ref. 27). Previously introduced robust laser interferometer (RLI) technology also demonstrated potential for electrical wiring health monitoring. Finally, previously introduced time domain reflectometry (TDR) is another method that can be used to measure changes in electronic wiring interconnect system characteristic impedance for detection of chafe, nicks, and corrosion defects (Ref. 34).

Monitoring the deterioration of components in electronic systems is much harder than mechanical systems (Ref. 35). There has been a thrust in recent years in developing methods and technologies for prognostics and health management of electronic components such as power system components, avionics, solder joints, etc. For diagnostics of electronic components expert systems, neural networks and fuzzy logic systems are used (Ref. 36). Bayesian diagnostic models are also used for diagnosis of faults in electronic systems (Ref. 37).

Solder joint faults are proving to be one of the main failure sources of electronic components. Thus, solder fatigue modeling and monitoring technologies are used to monitor small cracks that develop and propagate in the microstructure of solder joints due to thermal loading and/or aging. The changes in the material microstructure due to aging are used by some researchers to predict remaining useful life of the solder joints of electronic components (Refs. 38 and 39). Other prognostic methods have been proposed for various critical electronic components including digital electronic boards (Ref. 40), silicon carbide packaging (Ref. 41), integrated circuits (Ref. 42), and power actuators (Ref. 43).

4.1.4 Hydraulics

Hydraulic systems are extremely important in regards to flight control, as they play a role in positioning the control surfaces in many aircraft. Therefore, a failure in the hydraulic system can prevent the pilot from having full control of the aircraft. Another area where hydraulic systems are used is in commercial aircraft landing gear. A failure in this system can cause problems when the pilot wants to extend or contract the gear. Linked closely with hydraulic systems that maneuver the control surfaces are actuators as they are often driven by hydraulics. One type of actuator is the electromechanical actuator. In normal operation these are driven by electric power, but in high-stress situations, during a jam, or when electric power to the actuator is disrupted, the hydraulic system supplies the power needed to operate the actuator.

One problem that can occur in the hydraulic system is called cavitation. This phenomenon occurs when the pressure at the pump inlet is lower than the vapor pressure of the fluid, and it causes bubbles to form in the system. It is ideal to avoid this situation if possible, as it increases wear on the system. Researchers have developed a neural network based algorithm to detect cavitation using as inputs the electric current supplied to the pump motor and a voltage that can be used to determine the operational speed and output flow of the pump (Ref. 44). The cavitation data could possibly be fed to an adaptive control system to help increase the operational life of the hydraulic system. Another method of monitoring the health of hydraulic systems involves a neural network scheme that performs a vibration analysis of hydraulic pumps. The algorithm uses the fundamental frequencies and harmonics of the pump

and determines if it is operating normally or in a degraded state (Ref. 45). This could be used in an adaptive control scheme to inform the pilot or maintenance technicians of the health of the system.

There are many types of hydraulic system faults that result in a small leak somewhere in the system. Small leaks can be present for a while before they cause larger problems, but if they are detected early it is possible to prevent these problems. One method for detecting these faults involves online model-based fault detection. Using the operational speed of the pumps, it is possible to determine the pressures that should exist at various points in the system. Models have been developed that use pump data and pressure sensors to determine if there are leaks in the system and their location (Ref. 46). Another part of the system that cannot be overlooked is the health of the tubes that carry the fluid. Some of the research in this area involves modeling the decrease in operational lifetime of tubes with scratches or other damage (Ref. 47).

4.1.5 Static and Dynamic Actuators

Very similar to the previous section on hydraulic systems in general, actuators play an essential role in adaptive control technology as they move the control surfaces. As discussed, the state-of-the-art technology in terms of actuators involves the use of electromechanical systems. One problem that can occur in these actuators is called ball jam where the moving part containing the ball bearing gets stuck somehow, preventing the control surface from moving. Detecting actuator failures would provide valuable input to adaptive flight control software, as it would help establish the set of useable control surfaces. The majority of detection and prognosis technology in regards to ball jam in electromechanical actuators (EMAs) is model based. Various modeling techniques are used to detect malfunctioning EMAs, as well as predicting the time to fail for the entire system (Ref. 48). Although models have been created, the majority of the work is still done by technicians on the ground. However, technologies are being developed that use flight control data and will be able to deliver gray-scale, as opposed to pass-fail, feedback to maintenance technicians. With this information, maintenance technicians will be better able to isolate problem areas with less chance of overlooking problems or dealing with false-positive responses (Ref. 49). Another technology being developed is hybrid electromechanical/hydraulic actuators, which allow for in-flight mitigation of ball jam. These actuators run mechanically in normal operation, but a parallel hydraulic system kicks in when extra power is needed because of heavy loads or a ball jam. It is not certain that the hydraulic system will fix the jam, but it is one method of in-flight mitigation (Ref. 50).

4.1.6 Environmental Control System

Although faults in the pressurization system might not be a direct cause of many accidents and incidents, it can have adverse effects on the flight crew, indirectly affecting their ability to control the aircraft. Currently, pressurization systems use either preconditioned air from the ground or bleed air from the engine, which requires a water separator. It is also noted that 61 percent of component failures in this system are related to the water separator, so a significant amount of risk can be reduced by focusing on this component. However, in the future this failure in particular may have a decreased relevance. As aircraft manufacturers move towards more electric aircraft, such as the Boeing 787, they may use electric fans to pressurize the cabin where no water separator is required. While these faults are eliminated, they would then need to focus more attention on electrical and wiring faults, and the power plant will need to produce four times as much electricity (Ref. 51). The most advanced technology in regards to air conditioning and pressurization faults is actually related to predicting the time to failure for components such as the water separator. This is in contrast to most cases, where detection and diagnostics are more advanced. Researchers have produced fairly extensive prognostic models predicting the failure of various components in the pressurization system using Weibull distributions. These distributions are based on a power law relationship in which the probability of failure increases with flight hours (Ref. 52). Information from these algorithms might be used to give the flight crew a metric that measure “risk of failure” for this system.

4.2 Adverse Conditions Involving Damage to a Structure or Component

4.2.1 Propulsion System

The propulsion system is an area of the aircraft that has always attracted a significant amount of research. One area that has specific applications for adaptive control technology is the fuel system. The majority of fuel system faults occur because of water condensation, which can be harmful in freezing temperatures, degrade performance in other situations, or clog filters due to sediment. There are very few diagnostic systems specifically for fuel systems and even fewer systems that can mitigate detected faults. The conventional method of fuel system management is via a central computer system that controls fuel distribution among various tanks according to the stage of flight. Researchers at Penn State University have developed an adaptive fuel filtering system with parallel pumps. Data is collected via pressure sensors and can be used to identify faults or clogged filters. Integrated logic can adjust the flow or use water from the water separator to back flush clogged filters. A successful integrated test of this system was performed using a test rig constructed with diesel engines (Ref. 53). Multiple groups are researching alternatives to the central computer system for fuel management that use distributed networks of sensors and microcontrollers. The microcontrollers are used to control the fuel pumps using input from the sensor network in order to achieve the desired distribution of fuel in the tanks. This network of smart sensors eliminates the need for a central computer (Ref. 54). One method of decreasing risk of fires in the fuel tanks is to replace electromechanical sensors, which have a higher risk of initiating combustion in flammable environments, with fiber optic sensors (Ref. 55). Another technology to decrease fuel-system-related fires involves detection of electrical faults in the fuel pumps. A retrofit device called a universal fault interrupter was approved for use on Boeing 737-NG and 757 aircraft in 2008. It is an electrical box that is installed adjacent to the electrical relay and can detect electrical faults in the fuel pump and will shut down the pump when the inlet is uncovered or in times of uncommanded pump operation (Ref. 56).

Bearing health is critical to the performance of turbomachinery. Diagnostic technologies for rolling elements are relatively well developed. Among these are stress wave analysis (SWAN), which provides real-time measurement of friction and mechanical shock in bearings. This high-frequency acoustic sensing technology filters out background levels of vibration and audible noise and provides a graphic representation of machine health (Ref. 57). Acoustic emission technologies are also utilized as an indicator for bearing stress. RLI, an alternative technology to acoustic emissions, has also demonstrated use for bearing health monitoring (Ref. 58). On the other hand, accurate prediction of remaining life of bearings remains a challenge. Novel techniques for remaining useful life (RUL) estimation for bearings are in development especially those targeting incipient faults (Refs. 59 to 62). “Smart bearings,” although still at development stage, is another novel technology. If successfully developed, these bearings will have a number of unique features such as having all sensory/telemetry data built into the bearing, and durability for higher temperatures, long life, and compatibility with the operating environment (Refs. 63 to 65).

The oil and lubrication system can have a part in causing significant damage in the propulsion system. The main problems associated with aircraft oil and lubrication systems arise from clogged filters, pressure anomalies, and water in the oil. Pressure anomalies can result from multiple causes including low levels of lubricant and clogged filters. The health of this aspect of the lubrication system is monitored by pressure sensors that relay information to the pilot, and pilots are trained to recognize and adjust for various situations (Ref. 66). Using data from pressure sensors, adaptive control schemes could be designed to recognize the cause of various anomalies and either adjust aircraft operation automatically or provide guidance to the pilot. Another method that might be used to monitor the loss of lubricant in an engine involves a vibration analysis of moving engine components. Different vibration signatures arise as the level of lubricant in the system varies. This method is currently used by the U.S. Army for light armored vehicles but might also be applied to aircraft (Ref. 67). Faults in the oil system, such as a clogged filter, are often indicators of failures in components lubricated by the system. For example, as a moving part is worn down over time, particulates accumulate in the oil that lubricates it, and this can clog the

filter. Also, more than just getting worn down, structural failures in components might cause larger pieces of debris to accumulate in the system. By analyzing the oil in the system for composition and size of particulates, information about the health of lubricated components and of the oil system itself can be obtained. In 1995, the U.S. Army mandated that its aircraft undergo this type of analysis on a regular basis (Ref. 68). A company, Jet-Care, has commercialized the process by charging operators to send in oil and filter samples for analysis. They send back results that include a diagnosis of system health and a prognosis for suggested maintenance to provide (Ref. 69). If real-time monitoring of engine oil particulates and debris were available, algorithms could be designed to recognize the wear state of various components and give this information to the pilot.

One control system that has caused problems in the propulsion system is the full authority digital engine control (FADEC) system. On some aircraft, FADEC software triggers a fault when excessive force is applied to the throttle. When this occurs, the fault mode holds the thrust level at the last known setting. In various cases where this occurred at full power, pilots have had to shut down engines in order to reduce thrust. One company that was affected by this problem was Eclipse. They incorporated software updates into their legacy fleet to fix this problem (Ref. 70). The very existence of a FADEC allows for adaptive controllers to use this engine control software to help control an aircraft when control surfaces fail. There have been a number of algorithms written that use variable engine operation to control the aircraft (Ref. 71). Another component of the propulsion system that has been known to cause problems is the vacuum system. In some aircraft, the vacuum system is responsible for powering instrumentation such as the attitude indicator. If a failure in the vacuum pump is not known to the pilot, he may still rely on the attitude indicator even though it is no longer displaying accurate information. In certain circumstances this can lead to a loss of aircraft control. If the failure is detected, and the pilot is aware of this failure, loss of control could possibly be avoided. One method for detecting faults in the vacuum system involves measuring vibration data from the bearings in the pump and comparing it to data from normal operating conditions. Anomalies can be a sign for a fault in the system (Ref. 72).

Another adverse condition in the propulsion system that can lead to a loss of control is an engine fire. The conventional method of fire extinction/suppression in aircraft engines involves discharging halon. Researchers are looking for alternatives to halon because of its environmental impact, however, many think it will not be feasible to replace on many legacy aircraft. One area of research involves designing a nacelle with fire-resistant composites (Ref. 73). Boeing has designed a system in which overheat sensors on various engine components are used to detect potential engine fires. A warning light and/or sound are triggered in the cockpit to alert the pilot, who is then able to disperse fire suppressant via a switch (Ref. 74). There have also been numerous studies that have used computational fluid dynamics (CFD) modeling to examine how droplets of fire suppressant will flow through an engine nacelle that include obstructions such as wire bundles, support structure, and other objects (Ref. 75). Similar efforts have investigated the spread of engine fires throughout the nacelle (Ref. 76). The results of these efforts could be used to design a control algorithm for a fire suppressant system. Based on the location of the fire (from sensors), and the most probable paths of suppressant and spread of the fire accounting for obstructions, an algorithm could decide the optimal discharge of suppressant from a multinozzle system.

4.2.2 Control Surfaces

There is a significant amount of technology currently being utilized for control surface fault detection. Frequently, the faults associated with control surfaces occur because of problems with the actuators or hydraulic systems that move the control surfaces and/or keep them in position. Excessive loads can also cause structural damage including cracks and fractures. The presence of one of these faults can mean that the control surface gets stuck at a certain trim, is more difficult to position, or becomes completely ineffective. Algorithms have been developed that use flight variables to detect these types of faults (Ref. 77). Once a fault is detected, flight control software can diagnose the specific component where the problem exists. Some systems have been designed that give this information to the pilot. More advanced algorithms have been developed that estimate the performance degradation and a new flight envelope in the presence of the failure. One algorithm of this type that was meant for UAVs also determines whether

the mission can be accomplished with the degraded performance or whether the mission must be aborted (Ref. 78). Additional research has been done that is specifically focused on the performance of autoland systems in the presence of a control surface fault. Because of the precision needed at landing, this phase of flight is particularly susceptible to problems resulting from loss of control caused by control surface faults (Ref. 79). Numerous groups have designed flight control software packages that incorporate neural networks for additional capabilities to be used in landing with control surface faults. Another interesting topic being studied is the effect of false identification of faults on performance. If a flight controller detects a control surface fault, but the control surface is working properly, the compensatory trims it calculates for the other control surfaces will actually cause degraded performance themselves. Currently, the focus of this research on fault detection is merely calculating the effects of this phenomenon and not working on any mitigating solutions.

4.2.3 Aerodynamic and Structural Damage

Just as faults in control surfaces can cause the conventional flight control inputs to produce unwanted maneuvers, structural damage to the aircraft can also cause unwanted aerodynamic effects. If these anomalies were known, they could be used as input to an adaptive control system to calculate the proper adjustments to control surface trims. The current state of the art in detection methods for fatigue cracks on the metallic airframe structure primarily involves on-ground inspections. In terms of current fleet operation, this assessment is performed manually as a part of routine maintenance, which means a crack might be present for a period of time before it is identified. Various probe technologies are currently being investigated that would allow technicians to detect cracks that would not otherwise be visible. One such technology is eddy current inspection (ECI), which is a new method that produces a magnetic field on a material's surface to detect cracks, corrosion, heat effects, and thicknesses. ECI is effective on metallic surfaces; however it is limited to the area directly below the instrumentation point (Ref. 57). For example, one probe uses eddy currents to detect fatigue cracks underneath fasteners (Ref. 80). For onboard detection, piezoelectric transducers (PZTs) could detect a crack via disruptions in stress waves sent through particular airframe structures in flight (Ref. 57). However, the feasibility of integrating this technology onto an aircraft is yet to be determined (Ref. 81). Acoustic emission (AE) is another technology that is used for surface and inner structure crack detection and localization. This nondestructive evaluation technique involves monitoring for the emission of high-frequency vibration (>100 000 Hz) as an existing structural defect (crack) is stressed from the static loading of the system (Refs. 64, 65, and 67). In addition, induced positron analysis (IPA) technologies can reliably detect and quantify tensile plastic strain damage induced by simulated and operational conditions in aerospace material specimens and components including metallic surfaces (Refs. 82 and 83). In the area of prognostics, numerous algorithms have been developed to predict the growth of cracks under various flight conditions (Ref. 84). Once a crack has been discovered, the current state of the art in mitigation normally involves patching and/or bonding with epoxy or selective reinforcement (Ref. 85). Some additional research has been done in terms of effective selective reinforcement and what type of fixes can be implemented to best slow the crack (Ref. 86). Still, none of these methods involve onboard solutions. The closest there is to an integrated solution does not really involve condition-based mitigation, but the use of materials through which cracks naturally propagate more slowly (Ref. 87). One method of conditional-based mitigation is dynamic controls that change the load spectra to lighten loads on fractured structures. This does not fix the crack but would help slow its progression until it could be fixed on the ground (Ref. 88).

The use of composite materials in structural design is becoming increasingly popular in aerospace applications because of the benefit of reduced weight without much compromise in strength and stiffness performance. Their increasing use has underlined the need to understand their principal mode of failure, delamination (Ref. 89). Delamination may occur in the form of microcracks and voids that usually leads to a macroscopic loss of stiffness and strength, which and may lead to a catastrophic structural collapse. Some technologies for detection and diagnosis of delamination encompass sensors that detect unanticipated events such as impacts, sensor technologies for detecting aging, and nondestructive

inspection (NDI) tools for flaw identification and damage characterization. Specific sensors developed for onboard impact detection include PZTs and fiber Bragg grating (FBG) ultrasonic structural health monitoring (SHM) sensors, which can locate the point of impact (Refs. 57 and 90). Once impact is detected, NDI tool images are used to study the damage region, and modally selective sensors (i.e., lamb wave sensors (Ref. 91)) are used to monitor further damage growth. Different damage growth prediction methods are finally employed to estimate the remaining lifetime of the structure. These include the linear elastic-fracture mechanics method, the cohesive-fracture model, and delamination-threshold load method (Ref. 92). Feature-based signal processing methods and data-driven classification techniques are also proposed for damage detection and prediction (Refs. 93 and 94).

4.3 Adverse Conditions Involving Control Upsets Related to Pilot Error or Another Cause That Cannot Be Regulated by Aircraft Technology

4.3.1 Electrical

Both military and commercial aerospace systems are becoming increasingly dependent on electrical power as systems move towards the more electric aircraft concept. This novel architecture relies on digitally controlled power distribution to provide power to flight critical subsystems such as avionics, fuel, etc. This increasing dependence on electrical power necessitates the development of new technologies for autonomous health management of electrical power systems. Power system faults cover a wide range of problems, some of which is covered under power electronics faults and wiring problems. So, in this section, the main focus will be on technologies developed for arc prevention and power management.

The arcing of electrical powered systems is a major safety concern to new and legacy aircraft. The advent of high-voltage direct current (dc) systems accentuates this problem. Thus, arc fault prevention methods and algorithms address this critical need for electrical power system prognostics and health management. Arcing faults occur as a result of chafing and cracking of insulation, dielectric breakdown, and looseness at terminal connections. Once arcing is initiated, damage may propagate to other conductors in the wire bundle. The discharge of arcing energy results in insulation damage, smoke events, the loss of adjacent wires in a wire bundle, and ignition of flammable materials and vapors. Such conditions have been estimated to result in approximately one unscheduled landing during an average day of air traffic worldwide and are the primary suspects in a number of catastrophic events. The most common technique used for arc fault prevention is thermal circuit breakers. Newer technologies developed for arc prevention include the arc fault circuit interrupting (AFCI) technology (Ref. 95), which relies on the use of arc fault circuit breakers as a supplemental protection against arc fault conditions in addition to the thermal overload protection provided by present generation circuit breakers. Solid-state devices are also proposed as a potential replacement for traditional thermal circuit breakers as a way of preventing arcing faults. These devices typically have longer life cycle, faster response time for overloads, and lower power dissipation when compared to thermal circuit breakers (Ref. 96).

There are also technologies developed for management of digital power distribution in general and more specifically, arc fault management. An example is the Aircraft Electrical Power Systems Prognostics and Health Management (AEPHM) program (Ref. 97) sponsored by the Air Force Research Laboratory (AFRL). Other arc fault management systems can monitor the operation of the loads. Examples include monitoring marker lights to flag failures, monitoring motors and actuators for acceptable current levels, and logging the time and duration of operation of loads (Ref. 96). Distributed power systems are another new technology. This technology is an alternative to traditional centralized power systems. It is based on locating the power control devices near the electrical loads to reduce the amount of power wiring. The control commands for this type of configuration are sent to the power control devices with a data bus. Making use of a distributed power distribution unit not only significantly reduces wire weight, but can lower installation and maintenance costs based on the reduction in the number of connections.

4.3.2 Severe Weather

Icing is one of the adverse events that has attracted a significant amount of research, spanning a range of interests for health monitoring and adaptive control. Starting with detection, the state of the art includes both the detection of icing conditions in the airspace using ground-based models, as well as in situ detection of ice accretion on the aircraft. Researchers at the National Center for Atmospheric Research (NCAR) have developed the forecast icing potential (FIP) algorithm, which uses data from the National Center for Environmental Prediction to calculate icing potential in the three-dimensional environment (Ref. 98). If integrated into the flight deck, this could be used by pilots to avoid areas of high icing potential. Another method of detection is a joint venture between NASA and the U.S. Army to use ground-based Ka- and X-band radar to locate icing conditions in cloud formations, but this has not yet been integrated into any flight systems (Ref. 99). One method currently being investigated for detection of ice accretion on the aircraft is TDR. With this method, electromagnetic waves are transmitted, and when they are received, the presence of ice is detected based on the dispersion on the waves. The thickness is also able to be determined. Currently, this technology is still in the feasibility study stage (Ref. 100). In terms of prognosis, there are numerous computational models that are used to predict the growth of ice both on the airframe and on surfaces in the propulsion system (Ref. 101). In addition to prognostic models of ice accretion, models also exist to predict the degradation of flight controls as icing conditions develop (Ref. 102). This type of data could be especially useful for flight control algorithms. In terms of mitigation, one method that has been found to be effective is actually a software change introduced by General Electric (GE) in 1996. They found that an engine flameout due to icing frequently occurred on descent between an altitude of 20 000 and 10 000 ft. GE changed the electronic control unit variable bleed value (ECU VBV) logic to increase ice extraction from booster core/inlet in this range of altitudes, and no events have occurred on aircraft where this change was made (Ref. 103).

There are currently many systems under development that may prove more useful to pilots than conventional weather radar in the cockpit. One system under development takes in information from various radar sources to provide an in-cockpit display of turbulence risk. One of the sources is the enhanced-turbulence (E-turb) radar that has been developed to detect all turbulence earlier than conventional weather radar (Ref. 104). Another technology under development is the Turbulence Autopilot Reporting System (TAPS). When the accelerometer on an aircraft equipped with this technology senses that turbulence is affecting flying conditions, it sends this information to computers on the ground where the severity of the turbulence can be calculated and sent out to in-cockpit displays on other aircraft (Ref. 105). Information from E-turb and TAPS is integrated into a single display that shows the risk of turbulent conditions and provides the pilot with more information than available with conventional weather radar. In 2002, an algorithm called the integrated turbulence forecasting algorithm (ITFA) was demonstrated. It is similar to the previous system in that it integrates various sources of turbulence data, but different in that it combines forecasting algorithms while the previous system used radar and aircraft performance data. This algorithm combined the capabilities of several turbulence forecasting algorithms into one code, and was tested with a group of meteorologists from United Airlines and dispatchers from Comair. It was found that the algorithm had a high level of usability, but that it had a fairly high rate of false positive predictions or predicted that severity was higher than the conditions that were found (Ref. 106). The output from these turbulence forecasting algorithms may possibly be used as input to flight control algorithms that calculate alternate trajectories and flight paths for pilots to better avoid turbulence. Algorithms have also been developed to estimate the reduction in airspace capacity due to adverse weather conditions. This will allow air traffic controllers a systematic way to adjust traffic patterns in areas where adverse weather is detected (Ref. 107). The Boeing National Flow Model of airspace traffic was used to measure the benefits of automation and improved weather forecasting when airspace capacity constraints are in place due to adverse weather. The concept evaluated was “Collaborative Flow Management,” which lets airlines optimize their own schedule using ground delays, cancellations, rerouting, or other means (Ref. 108).

4.3.3 Inadequate Attitude/Airspeed and Stall/Spin

A large number of possible faults involve the propulsion system and can lead to inadequate attitude/airspeed and stall/spin. If these conditions are detected, an adaptive flight control system can assist the pilot on returning to normal flight conditions. Technologies developed to monitor and prevent engine stall and faults in turbomachinery cover a wide variety of techniques. These include monitoring of specific vibrations in an individual blade to prevent the potential of catastrophic failure and prevent turbine downtime. Specific technologies for blade vibration monitoring include eddy current, optical, and capacitive sensors and algorithms that can process and fuse data from these sensors. Eddy current sensors are used for the purpose of gas turbine engine stability monitoring including stall detection, and blade harmonics. Microwave blade tip sensors are another technology that has considerable promise as a state awareness technique for the monitoring of rotating blades and disks. These sensors produce information-rich waveforms of the blade end geometry. Foreign object damage (FOD) detection systems entail a suite of new technologies. These include systems for detecting and analyzing ultrasound or stress waves emitted when an object enters the intake of a turbine engine and impacts one or more of the blades in the engine. Upon detection, the FOD detection system can immediately inform the operator, inform another electronic device (computer, etc.), and/or latch the event for review by maintenance personnel. The Joint Strike Fighter Prognostics and Health Management (JSF PHM) Program employs this technology.

Debris monitoring is another class of technologies applicable to engine health monitoring. The fundamental principle of gas path debris monitoring is to sense the electrostatic charge associated with debris present in the gas path of jet engines or gas turbines. Gas path debris monitoring technologies are critical for propulsion health management. Engine Distress Monitoring System (EDMS) and Ingested Debris Monitoring System (IDMS) are two technologies demonstrated on the Joint Strike Fighter (JSF) seeded fault engine test (SFET) program. Tomography is another technology based on hyperspectral absorption spectroscopy for temporally and spatially resolved temperature and water concentration measurements in practical combustion devices.

Surface acoustic wave sensors are another technology with demonstrated application to turbine engines. These sensors can be used as multifunctional temperature/pressure sensing devices for turbine engine test validation. Finally, the development of harsh environment sensors is also critical to engine health management. Notable technologies in this class include silicon carbide sensor devices that can work at high temperatures up to 500 °C. These sensors can be used for sensing motion, acceleration and gas flow, gas composition, and radiation detection. Another harsh environment sensor development for propulsion system applications is ceramic sensors, which are not limited thermally when compared to traditional metal thin film sensors.

4.3.4 Pilot

Technology in the cockpit can play a large role in helping a pilot keep an aircraft in control, as well as help regain control if it is lost. For example, if a pilot is not aware of a failure that affects control surfaces or actuators, the flight envelope can be altered and a maneuver that would be within the limits of normal operation may cause a loss of control. If a pilot does not know that a control surface on one wing is stuck, they may use the control in an improper manner. The procedure to command the plane to pitch up might cause pitch that is less than desired, and also a slight roll. In one study of adaptive flight control systems, a pilot survey indicated that two improvements pilots were interested in involved calculation of flight envelopes and better in-cockpit information displays of this type of information (Ref. 17). Training can also reduce pilot error. The FAA released a report that stated that a lower level of English language proficiency can lead to communications problems in English-speaking airspace, and this has led to a few accidents. More stringent language requirements for pilots flying in areas where the language used by air traffic control is not their primary language would mandate more training for less proficient speakers and eliminate accidents (Ref. 109). Other studies have been conducted that show that training can lead to pilots using in-cockpit technology to a greater benefit. One FAA report studied the differences in pilots' usage of weather radar before and after training. With no training, the pilots fell into two distinct groups.

The first group used the weather radar to stay as far away as possible from adverse weather. The second group exhibited a potentially hazardous behavior in which they used the weather radar to keep their deviation from their planned flight path as small as possible. The latter is potentially hazardous behavior, as weather conditions are unpredictable and can change very quickly. After training, the prevalence of this behavior was only 44 percent of the original amount compared to a control group, and the average distance from the storm for the pilots that took the training also increased by a factor of 3 (Ref. 110). A possibility for new adaptive control technology is highlighted by this study. It might be possible to design a flight control algorithm in conjunction with the weather radar that calculates optimal alternative flight path for the pilot when adverse weather is experienced. This optimization would keep pilots from being overly conservative in their avoidance of adverse weather, but also hopefully prevent them from being too aggressive.

5.0 Conclusion

A general discussion of state-of-the-art technologies in flight control was presented. A more specific look at the state of the art of flight control as related to the 13 adverse conditions was also given. This specific information was not all completely related to flight control, but often consists of detection or modeling technology that could make an ideal input for future flight control schemes.

In general, there were two distinct methods for implementing adaptive flight control systems. In the first method, the system assists the pilot in operating the aircraft in a degraded state by providing additional information on the degradation state of the aircraft and then makes calculations relating to alternative use of controls or alternative maneuvers. The second type of implementation involves no change in the pilot's method of operation in relation to a nominal operating environment. The adaptive control system takes the nominal control inputs given by the pilot, performs calculations based on the degradation state of the aircraft, and sends alternative commands to the vehicle control surfaces and/or propulsion system. This method is very different than the first, as the pilot is not required to alter his/her operation of the plane due to the degradation.

There is much more research being done on failures and degradation of specific components in relation to adaptive control systems. Although component research is important, as it can provide better input data into adaptive control systems, there is still much more work that can be done to advance the state of the art of the actual adaptive control systems. In regards to the two methods of implementing adaptive control, the trend is that the state of the art is moving in the direction of systems in which the pilot operates the aircraft the same in both nominal and off-nominal conditions where the adaptive control system itself alters the commands that go to the control surfaces and propulsion system when operating in an off-nominal state.

As the scope of this study would make an indepth discussion of each technology infeasible, readers are encouraged to examine the references for more detailed information on the technologies summarized in the various sections. It is also acknowledged that only a small selection of current work in the various fields could be discussed in the paper. Additional references not cited in the paper that may offer a broader perspective of the current technologies are available by contacting the author.

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Appendix A.—Acronyms

AE	acoustic emission
AEPHM	Aircraft Electrical Power Systems Prognostics and Health Management
AFCI	arc fault circuit interrupting
AFRL	Air Force Research Laboratory
AirSTAR	Airborne Subscale Transport Aircraft Research
ASIAS	Aviation Safety Information Analysis and Sharing
ASRS	Aviation Safety Reporting System
AvSAFE	Aviation Safety Program
CFD	computational fluid dynamics
ECI	eddy current inspection
ECU VBV	electronic control unit variable bleed valve
EDMS	Engine Distress Monitoring System
EMA	electromechanical actuator
E-turb	enhance turbulence
FAA	Federal Aviation Administration
FADEC	full authority digital engine control
FBG	fiber Bragg grating
FIP	forecast icing potential
FOD	foreign object damage
GE	General Electric
GPS	Global Positioning System
IDMS	Ingested Debris Monitoring System
IFCS	Intelligent Flight Control System
IPA	induced positron analysis
IRAC	Integrated Resilient Aircraft Control
ITFA	integrated turbulence forecasting algorithm
JSF	Joint Strike Fighter
JSF PHM	Joint Strike Fighter Prognostics and Health Management
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NDI	nondestructive inspection
NTSB	National Transportation Safety Board
NWS	nose wheel steering
PASD	pulse-arrested spark discharge
PZT	piezoelectric transducers
RAVEN	Real-Time Indoor Autonomous Vehicle Test Environment
RLI	robust laser interferometer
RUL	remaining useful life
SFET	seeded fault engine test
SHM	structural health monitoring
SWAN	stress wave analysis
TAPS	Turbulence Autopilot Reporting System
TDR	time domain reflectometry
UAV	unmanned aerial vehicle

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188		
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1. REPORT DATE (DD-MM-YYYY) 01-09-2010		2. REPORT TYPE Technical Memorandum		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Assessment of the State of the Art of Flight Control Technologies as Applicable to Adverse Conditions			5a. CONTRACT NUMBER		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Reveley, Mary, S.; Briggs, Jeffrey, L.; Leone, Karen, M.; Kurtoglu, Tolga; Withrow, Colleen, A.			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER WBS 645846.02.07.03.16		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191			8. PERFORMING ORGANIZATION REPORT NUMBER E-17212		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001			10. SPONSORING/MONITOR'S ACRONYM(S) NASA		
			11. SPONSORING/MONITORING REPORT NUMBER NASA/TM-2010-216226		
12. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified-Unlimited Subject Category: 03 Available electronically at http://gltrs.grc.nasa.gov This publication is available from the NASA Center for AeroSpace Information, 443-757-5802					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT Literature from academia, industry, and other Government agencies was surveyed to assess the state of the art in current Integrated Resilient Aircraft Control (IRAC) aircraft technologies. Over 100 papers from 25 conferences from the time period 2004 to 2009 were reviewed. An assessment of the general state of the art in adaptive flight control is summarized first, followed by an assessment of the state of the art as applicable to 13 identified adverse conditions. Specific areas addressed in the general assessment include flight control when compensating for damage or reduced performance, retrofit software upgrades to flight controllers, flight control through engine response, and finally test and validation of new adaptive controllers. The state-of-the-art assessment applicable to the adverse conditions include technologies not specifically related to flight control, but may serve as inputs to a future flight control algorithm. This study illustrates existing gaps and opportunities for additional research by the NASA IRAC Project.					
15. SUBJECT TERMS Flight safety; Aircraft safety					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 30	19a. NAME OF RESPONSIBLE PERSON STI Help Desk (email:help@sti.nasa.gov)
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPHONE NUMBER (include area code) 443-757-5802

