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Flight Control Century: Triumphs of the Systems Approach

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Introduction

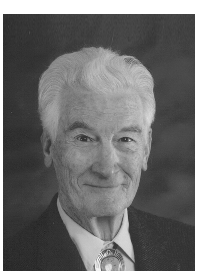
SPEAKING before the Western Society of Engineers in 1901, Wilbur Wright said

> Men already know how to construct wings or aeroplanes, which when driven through the air at sufficient speed, will not only sustain the weight of the wings themselves, but also that of the engine, and of the engineer as well. Men also know how to build engines and screws of sufficient lightness and power to drive these planes at sustaining speed. . . . Inability to balance and steer still confronts students of the flying problem. . . . When this one feature has been worked out, the age of flying machines will have arrived, for all other difficulties are of minor importance.

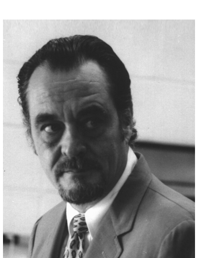
No one among our readers would doubt that, in the century since then, the "age of flying machines" has indeed arrived. At the same time a certain inability to always reliably "balance and steer" still confronts us.

The story of technology we will sketch here is not inevitably one of a cumulative progression, or even necessarily one of the survival of the fittest. Instead, the history of aviation, as we see it, is one of the conciliation of courage and curiosity, challenge and response, and practical ingenuity and learning. Although not always recognized as such, flight control is a systems discipline at the leading edge of aeronautics. Indeed, the triumphs and pitfalls of the systems approach to flight control design may be traced from before the first flight to the present day and even extended in imagination to the future. Thus, what we intend to discuss are rises, falls, and saddle points in the fortunes and understanding of the feedback systems approach to the design of feedback control systems for piloted aircraft.

Whereas the Wright brothers are justly famed for their priority in many fields of aviation, their most notable contribution was the implicit appreciation that the secret to the control of flight was feedback. From their tethered and glider experiments, they recognized that the human pilot, operating on perceived feedback signals, that is, the pilot's attitude with respect to the ground, position with respect to a desired landing point, etc., should be able to operate the controls to stabilize, control, and guide the aircraft in a desirable fashion. They recognized that the frustrating search for inherent stability that had obsessed their forerunners might well be abandoned



Duane McRuer received his undergraduate and graduate education at the California Institute of Technology. After associations with Northrop Aircraft, Inc. (1948–1954) and Control Specialists, Inc. (1954–1957), he cofounded Systems Technology, Inc. (STI). At STI he was President and Technical Director (1957–1993), then he became Chairman. Since 1950, his research has been focused on aerospace, ground vehicle, and human pilot dynamics, automatic and manual vehicular control, and vehicle flying/handling qualities. This has been documented in more than 130 technical papers and seven books, including *Analysis of Nonlinear Control Systems* (with Dunstan Graham) and *Aircraft Dynamics and Automatic Control* (with Irving Ashkenas and Dunstan Graham). He has been involved with applications of these topics on more than 50 aerospace and land vehicles and has five patents on flight control and stability augmentation systems. He has also been a Regent's Lecturer at the University of California Santa Barbara and the 1992–1993 Hunsaker Professor at Massachusetts Institute of Technology. His past service on various government and professional society activities include terms as Chairman of the National Research Council Aeronautics and Space Engineering Board and the AIAA Technical Committee on Guidance and Control, and he is a long-term member of the NASA Advisory Council. Besides being an Honorary Fellow of the AIAA, he is a member of the National Academy of Engineering. Other honors include the California Institute of Technology Distinguished Alumni Award (1983), the NASA Distinguished Public Service Medal (1991), the AIAA Mechanics and Control of Flight Award (1970), and the Franklin Institute's Levy Medal (1960).



Dunstan Graham earned B.S.E. and M.S.E. degrees from Princeton University in 1943 and 1947, respectively. After working briefly in the Controls Group at Fleetwings in 1943, he joined the U.S. Army Air Force where he became a navigator. In 1947 and 1948 he was an aerodynamicist with The Boeing Airplane Company and then was engaged in flying qualities research at the Cornell Aero-Laboratory. From 1950 to 1955, he was with the Air Force's All-Weather Flying Division, ultimately responsible for a broad flight research program in the mechanics of aircraft response to control, automatic pilots, radio and radar aids to navigation, and deicing. At Lear, Inc., between 1955 and 1959 he was Chief Engineer, flight controls, in charge of development of the automatic flight control equipment for, among others, the KC-135, Sud Caravelle, SAAB J-35, F-104, and F-5. In 1959, he was appointed to the faculty of Princeton University and, simultaneously, became a Technical Director of Systems Technology, Inc. (STI). As a Professor of Aeronautical Engineering at Princeton he taught and was responsible for research and course development in automatic control, air transportation, automatic control and guidance, autoland, air traffic control, and navigation and played an important role as a teacher and mentor of many outstanding graduate students. As a Technical Director at STI during the same period, he conducted and directed research in human pilot dynamics, aircraft and spacecraft control, and theory of nonlinear and time-varying systems. In 1980, he retired from both his Princeton and STI positions and became an independent consultant. He was a chair of the AIAA Technical Committee on Guidance and Control and served on a number of NACA and NASA advisory committees as well as being a Special Advisor to the U.S. Air Force Aeronautical Systems Division. Starting in 1953 he frequently collaborated with Duane McRuer on books, papers, projects, and technical reports. Dunstan Graham was an Associate Fellow of the AIAA. He died in July 1992.

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if only the pilot were provided with sufficiently powerful controls with which to balance and steer: in a more modern context, that the human pilot, operating on feedback signals, could use the controls to stabilize a neutrally stable or even an inherently unstable aircraft. The Wrights proceeded to build and fly this aircraft configured for good control. As control specialists, we delight in the recognition now accorded to the Wright's invention of feedback stabilization and control. They were indeed students of all aspects of the flight system.

For the Wrights, the flight control system sensors, equalizers, and actuators were human, and the surface control system was mechanical. Equipment used since then in flight control systems has progressed through several technological generations. The first successful systems were largely pneumatic, sometimes with electrical elements in secondary roles, for example, to run gyro wheels. By the late 1940s, the technology was all electric, from sensors to servos, with carrier circuits at intermediate stages. In the early 1950s, dc operational amplifiers and electrohydraulic servoactuators became prominent, especially with stability augmenters. Tubes and magnetic amplifiers, succeeded by operational amplifiers, were ultimately morphed to today's integrated circuits and photonic devices.

Across these generations, the functions performed by the flight control systems have expanded as permitted by the advances in technology. An overview of the development and approximate first appearance of functions is given in Table 1, although no claim is made for completeness. The time lines relating when particular system functions could be affected by feasible physical means (Table 1) form one of our underlying historical themes to which we shall refer from time to time.

Choice of Eras

Our history of flight control as an often cyclic evolution of challenge, response, ingenuity, and learning may be divided conveniently into five eras: From earliest times to 1901, we call the era "early dawn." The epoch from 1901 to approximately 1931 we call the "classical age," the heritage of the Wright brothers. From 1931 to 1956 we call "before yesterday," whereas from 1956 to 1981 we call "only yesterday." (We borrow here the evocative phrases of Frederick Lewis Allen, editor and social historian.) Finally, from the early 1980s to today we call "since yesterday."

To supplement our theme of function development during these eras, we shall delineate a second underlying theme: the early independent development of theory and practice in quite different but relevant technologies, their subsequent confluence, and then the specialization and professionalization, which may have produced a new compartmentalization of thought and a possibly dangerous empiricism.

Naturally, in the space allotted to us, we shall be able to present only typical snapshots. We shall hope that these are illustrative. For many other examples that could be cited, see the excellent history by Howard.[1]

Early Dawn: Earliest Times to 1901

The early dawn era was characterized by a record of relatively rare individuals who contemplated dynamic aircraft stability and flight control. In a previous paper,[2] we have pointed to the contributions of Lanchester and Maxim.[3] Inspired by Maxwell,[4] Routh[5] provided a theoretical background for "inherent" stability, but for a long time his work was unremarked except possibly by transcendental mathematicians.

Classical Age: 1901–1931

By the end of 1901, the Wright brothers had made their invention. Figure 1 illustrates the 1902 glider in full stable flight under manual control. This was the successful reduction to practice on which the brothers' famous patent was based.[6] We suspect that their skills and technical talents as bicyclists, subsequently conditioned by their many trials in the turbulent winds of Kill Devil Hill, with consequent modifications to their configurations, lead to their great emphasis on neutral stability in the lateral axis and manual control to create a stable man–machine system. Until about 1931 any triumphs of aviation, including the use of the airplane during World War I and the early development of air transportation, were achieved with manual control and certainly without the use of higher mathematics. These triumphs were the heritage of Wilbur and Orville Wright.

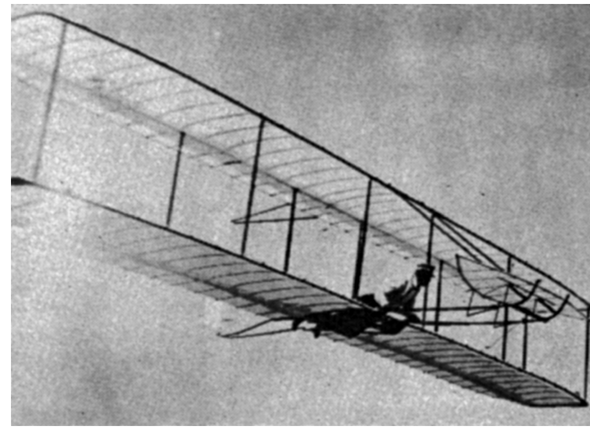

Fig. 1 Wright glider 1902 (Smithsonian Institution photograph A42413-E).

Aircraft engineers quickly learned to secure a desirable bare minimum of three-axis static stability with respect to the relative wind using algebra and rules of thumb based on empirical data. The subsequently enduring position was formally presented to the Engineering Society of Glasgow University by the designer Barnwell very early in the fateful year 1914.[7]

The crisis of World War I inaugurated a period of unparalleled achievements in aircraft design by the first generation of aircraft design engineers following the founding visionaries and inventors. Their progress can be illustrated by some simple comparisons with the baselines established by the Wrights. The 17 December first day's longest flight was 852 ft, attained in 59 s. By 5 October 1905, the Wrights were airborne for over 38 min and traveled more than 24 miles. Wilbur's longest flight in France on 18 December 1908 in a Wright A was 2 h, 20 min over a distance of 78 miles. To provide perspective for the advances made in just over a decade, on 14–15 June 1919, John W. Alcock and Arthur W. Brown flew a modified Vickers Vimy bomber nonstop from St. John's, Newfoundland to Clifden, County Galway, Ireland. The flight of 1900+ miles was concluded in less than $16\frac{1}{2}$ h, averaging approximately 115 mph. The Vimy's top speed was about 110 mph, with best cruise at 80 mph, so that the winds were favorable indeed. Traversing the Atlantic partly at night and often in cloud, with a primitive suite of instruments that was nowhere near that required for safe instrument flight rules (IFR) flight, was an absolutely marvelous feat of airmanship.

In parallel with the aircraft design engineers that dominated the classical era, two types of research engineers were also actively dealing with flight control problems, the dynamic theoreticians and the tinkerer/inventors. They were busy, and ultimately productive. However, because of the emphasis on, and availability of solutions for, adequate manual control, there was no readily perceptible requirement for their efforts.

Scientists/Theoreticians

In the year of the first flight, we have the first major contribution of the pioneer theoretician, G. H. Bryan (see Ref. 8). He persevered and produced the classic book on aircraft stability and control.[9] For starters, he studied the linearized motions of the airplane, assuming small perturbations; discovered the separation of the longitudinal and lateral motions; invented stability derivatives, etc. Only the orientation of his axis system differed from modern usage. Shortly after that, Bairstow and Melvill Jones, at the National Physical Laboratory in Great Britain, measured the stability derivatives and calculated the motions of practical airplanes (see Ref. 10). In the period from about 1910 through the early 1930s, there was an enormously productive effort in Great Britain. People calculated the stability of aircraft, calculated the response to disturbances, calculated the response to

Table 1 Significant development of automatic flight control functions

Era / Function:	Body-fixed axis damping and wind attitude stability	Earth-attitude stability	Pilot intervention	Parameter adjustment (or insensitivity)	Flight path control	Redundancy management	Expansion of flight control functions
Dawn		Maxim, I-axis, 1891	Attitude command	Airspeed vane			
1901							
Classical	See Table 2						
1931							
Before Yesterday	HS127 damper B-49 "Electronic Tail" B-47 yaw damper F-89 sideslip stability augmentor F-102 trim shifter F-104 3-axis damper, etc.	Siemens and Askania course controls Mk I, 2-axis Sperry A2/A3, 3-axis All-electric, 3-axis auto-pilots	3-knob attitude adjust Single-knob turn control All-attitude maneuvering Control stick steering	Force servos Dynamic pressure compensators	Altitude control Approach coupler Autothrottle Fire control CSTI TO and climb guidance Mach hold	Dual hydraulic surface actuators Single-channel monitors Active circuit redundancy	Punched card guidance reference and aircraft configuration control (multi-mode)
1956							
Only Yesterday	Active control: relaxed static stability, maneuver en-hancement	Stable platform references Strap-down INS tie-in Redundant sensor complexes	Stall avoidance Fly-by-wire Large value limiting and full flight envelope "stretching"	Air data tie-in Multiple accelerometer feedback Self-adaptive gains	Snark optimum climb cruise control Auto-land Terrain following Terrain avoidance "Corridor" flying, including VTOL transition and Shuttle reentry Collision avoidance	Mid-value logic Trident, FOFS Quad-redundancy FOFOFS Digital computer redundancy management: self-monitoring, parity check, fault isolation, reconfiguration, pre-flight test, failure recording	DLC and side force control; control "purification" Active control: relaxed static stability, span load modification, elastic mode suppression, vibration suppression, ride smoothing, flutter suppression
1981							
Since Yesterday					Total flight management (GPS)	Onboard surveillance	Total flight management

applications of controls, made full-scale in-flight measurements to show that the responses were correct, etc.

Perhaps most notable from the automatic control standpoint during this period are the efforts of Gates, Garner, and Cowley. Gates in 1924 assumed that the controls were moved according to certain laws, that is, in proportion to certain output variables and their derivatives.[11,12] He stressed that good stability was not enough and that it was essential also to consider the amplitudes of the several modes of motion. In 1926 Garner analyzed lateral–directional motions of an airplane under the influence of feedback control.[13] He specifically pointed out that the movements of the controls might be regarded as made either by the human pilot or by some mechanical means. Garner further had the wit and vision to make provision in the theoretical treatment for lag in the application of controls and was able to point to a qualitative correspondence between his analytical results and flight tests of an Royal Aircraft Establishment (RAE) automatic rudder control that had appreciable lag. Then in 1928, Cowley proposed more elaborate methods of taking into account the time lag in the application of control, successfully treating both a pure time delay and a second-orderlag.[14]

It now seems surprising that these papers are not given more prominence in accounts of the development of the theory of automatic control systems. They seem, in fact, to have fallen into a deep dark hole. Perhaps they were simply too far ahead of their time; perhaps, on the other hand, it was only in Great Britain, where automatic flight control system development at this time was the responsibility of a government research establishment, that it was thought to be desirable to make response calculations in connection with the design of practical systems. It cannot be said that the people who were developing autopilots paid no attention to the theoreticians; they were sitting across the hall from one another and they did know what the theoreticians were doing. For example, as early as 1937, we have the paper by Meredith and Cooke.[15] They crossed the lines by describing both the practical and theoretical aspects of autopilot development.

By 1935 when Melvill Jones surveyed stability and control,[16] the classical approach initiated by Bryan[4] was well established but very little used. The theory of small perturbations, the examination of stability, the ability to calculate the time history in response to disturbance or to the application of control, the full-scale experiments (conducted with the F.2B "Bristol Fighter," designed by the aforementioned Barnwell) that led to the conviction that the theory of infinitesimal motions was practical for the prediction of stability of motion, etc., were all meticulously and elegantly covered. The effects of variations in the configuration of a typical airplane were traced via their influence on the derivatives to the result in terms of motion characteristics. Furthermore, these results were appreciated not only in terms of the solutions to specific numerical examples, but more generally as approximate solutions given in terms of the dominant literal stability derivatives. However, Melvill Jones did not cover feedback control of the aircraft's motions, although he wrote a decade after Gates' initial efforts. He recognized[16]

> It is probable that mechanical control will become increasingly popular for large long-distance aero planes, and for anything in the nature of pioneer work in this subject, calculations of this kind are essential. No mention of the methods of extending the calculations to deal with mechanical control will, however, be found in the present work since this is still a matter of research and what little has been published is mainly of a controversial nature.

He did recognize that "work of the type discussed here forms an essential introduction to the study of mechanical control." Melvill Jones's comment on the application of the theory that he did cover, that is, aircraft-alone dynamics, was as follows:

> In spite. . . . of the completeness of the experimental and theoretical structure. . . it is undoubtedly true that, at the time of writing, calculations of this kind are very little used by any but a few research workers. It is in fact rare for anyone actually engaged upon the design and construction of aero planes to make direct use of [such] computations. . . , or even to be familiar with the methods by which they are made. . . . In my own opinion it is the difficulty of computation. . . which has prevented designers of aero planes from making use of the methods. . . .

We shall refer again to this quotation. By extension, it makes matters clear about automatic flight as well. Procedures for treating automatic flight control systems involved factoring quintics or higher degree polynomials, whereas the rigid-body aircraft-alone equations were only quartics. Because of the limitations of the procedures then available, it is easy to see why very few people were interested in pursuing design calculations in any depth.

The situation was hardly altered during the next 10 years. In spite of the introduction of the method of operators, which did reduce the labor of computation, and in spite of earnest efforts to make the techniques as simple and general as possible by introducing a nondimensional notation, and by summarizing information on the stability factors in convenient charts, and, further, in spite of hortatory expositions of the theory, designers of airplanes continued to disdain dynamic stability analysis.

Tinkerers/Inventors

Beginning in 1909–1910, Elmer Sperry, later assisted by his sons Laurence and Elmer A. Sperry Jr. and other associates, conducted a series of experiments in the control of aircraft flight using gyroscopic references. The story of the 1912–1914 Sperry airplane stabilizer has been well told and illustrated elsewhere.[1,2,17,18]

Other inventors were also very active. From about the time that flying came to Europe, people tried or conceived of all kinds of automatic stabilization for an aircraft. They used the feedback of speed, of incidence (what we now call angle of attack), of inclination (what we now call pitch angle), of its derivative, etc., and they attempted power amplification and servomechanism drives of the control surfaces. Table 2, adapted from Haus,[19] provides a shortened survey of these extensive efforts. Perhaps a sad part of all of this vast experimentation on feedback control of aircraft was that few people had any use for it. The designers of aircraft, following such rules as those exemplified by Barnwell,[7] had learned how to provide enough stability so that the pilots could handle the airplane, and nobody needed automatic feedback control.

Nevertheless, firms specializing in automatic flight control persevered and continued their efforts. Writing in 1931, Sperry described[20] a culmination: the Sperry automatic pilot. This unit was ordered by Eastern Air Lines for its Curtiss Condor airplanes. The Condor was the first American-designed luxury airliner. (One version was a sleeper.) An age of convenient, comfortable, and affordable air transportation seemed to be at hand. The automatic pilot was there.

That air transportation was to be swift and that it would span the globe was also foreshadowed in 1931. In 1929, the German airship Graf Zeppelin had made a world circuit record of $21\frac{1}{3}$ days. On the morning of 23 June 1931, pilot Wiley Post and navigator Harold Gatty took off from New York in the sleek Winnie Mae. Post and Gatty landed in New York again 15,477 miles and 8 days, 15 h, and 51 min later. They had been around the world via Europe, Siberia, Alaska, and Canada.

Before Yesterday: 1930s–1956

The year 1932 saw the introduction of The Boeing Company Model 247, the first of the all-metal, unbraced wing airliners. These were to drive the likes of the Condor from the skies. United Air Lines ordered them with improved Sperry A-2 automatic pilots.

A heroic demonstration of capabilities was given by yet another flight by Wiley Post, this time alone. Between the 15th and 22nd of July 1933, he flew the Winnie Mae around the world in a total flying time of 115 h, $3\frac{1}{2}$ min. Over an almost identical route, he nearly halved the elapsed time. Post gave the automatic pilot, Mechanical Mike, credit for contributing to the success of this incredible flight. He was able to nap, in-flight, while the airplane was under automatic control. This showed a touching faith in the reliability of the equipment. The *New York Times* called

Table 2 Early flight control inventions

Feedback variable	Control	Inventor	Date	Actuating means
Speed U	Elevator deflection	Budig	1912	Mechanical connection to sensor
		Etévé	1914	
Incidence α	Elevator deflection	Etévé	1910	Mechanical connection to sensor
Inclination θ	Elevator deflection	Regnard	1910	Electric type of servo
		Sperry	1912	Air-turbine-driven clutch servo
		RAE	1927	Pneumatic servo
Angular velocity $\dot{\theta}$	Elevator deflection	Girardville	1910	Mechanical connection to sensor
Direction of apparent gravity, $g \sin\theta + \mathrm{d}U/\mathrm{d}t$	Elevator deflection	Moreau	1912	Electric-motor-driven clutch servo
Speed U and inclination θ	Elevator deflection	Marmonier	1909	Unknown type of servo
Bank angle ϕ	Aileron deflection	Sperry	1912	Air-turbine-driven clutch servo
Heading Ψ	Rudder deflection	RAE	1927	Pneumatic servo

the flight "a revelation of the new art of flying." The news report added:

> By winning a victory with use of gyrostats, a variable pitch propeller, and a radio compass, Post definitely ushers in a new stage of long distance aviation. The days when human skill alone, an almost birdlike sense of direction, enabled a flyer to hold his course for long hours through a starless night or over a fog are over. Commercial flying in the future will be automatic.

The then-approaching World War II forced the further development of automatic pilots and encouraged elaboration of the theory, but they remained largely separate lines of endeavor. What happened, in the United States anyway, was the very rapid development of the all-electric automatic pilot. The Sperry 1914 autopilot was electric in its sensors and pickoffs but not in its actuation. Subsequently, the Sperry Company went to pneumatic pickoffs, pneumatic power for the gyroscopes themselves, and hydraulic actuation. The all-electric autopilots, which were developed by a number of firms in the United States, Honeywell, entering the business[21] with the C-1, as well as Bendix and Sperry, were in fact all-electric in the sensors, pickoffs, power amplification, and actuation. The flexibility associated with this means of mechanization permitted rapid introduction of a number of novel features, a single-knob turn control (replacing three different knobs), erection cutout, altitude and heading as outer loops superimposed around the previous pitch and bank loops, synchronizers, rate gyros or electrical compensation to increase damping, that all appeared in practical production flight hardware within a very short time.

The functions that now could be performed (Table 1) exploded in number. Again, almost all of this was accomplished by the tinkerer/inventors operating with little or no theoretical backup. Like the aircraft, the stability and control properties of the closed-loop systems were evaluated in flight tests, and flight control equipment was also designed with the aid of extensive full-scale testing. The excessive dimensionality mentioned by Melvill Jones[16] was still present, and cut-and-try did the job: indeed, so well that all of the elements of a modern automatic pilot were now at hand.

Because manual control was central, flight control system (FCS) evolution during the classical and before yesterday eras was a gradual incremental progression in the development of more and more elaborate mechanical contrivances invented to meet the needs of ever-expanding aircraft size and performance characteristics. Partly to avoid patent problems, wing warping was very early on replaced by surrogates. Then, as payloads and sizes increased, schemes were devised to reduce the forces that the pilot needed to develop for control. Control surfaces that included aerodynamic balance, flying-tabs, servo-, spring-, and linked-tabs, spoilers, etc., were introduced to satisfy the pilot's load-alleviation needs. These were terminal effectors actuated via long cable runs and push–pull rod sequences that were often routed through the airframe in mysterious ways. Special features such as cable tension regulators added to the mechanical complexity. All of these devices served their intended purposes, although the insidious presence of friction and an extensive need for careful rigging and adjustments were often viewed as plagues.[22]

Robot-Piloted Plane Makes Safe Crossing of Atlantic

No Hand on Controls From Newfoundland to Oxfordshire—Take-Off, Flight and Landing Are Fully Automatic

By ANTHONY LEVIERO

Special to THE NEW YORK TIMES.

WASHINGTON, Sept. 22 — A Douglas C-54 Skymaster with a mechanical brain landed without human aid near London today after a robot directed hop from Newfoundland.

The revolutionary flight across the Atlantic, effected by the push of the button, was hailed by Air Force leaders as a feat with vast new possibilities for war and peace.

The robot Skymaster, only one of its kind in the world, lifted itself off the field at Stephenville, Newfoundland, at 5 P. M. Eastern standard time, yesterday. This morning, 10 hours and 15 minutes later, the Skymaster eased itself onto the field at Brise Norton, forty miles west of London. The ship had flown 2,400 miles.

Fourteen crew men and observers were aboard the unique plane, but not once was it necessary for any of them to take a control or to intervene in any way with the mechanically prescribed course.

Delicate instruments, which did not falter, guided the ship, Air Force spokesmen said. Two ships somewhere in the Atlantic furnished bearings to the Skymaster's brain. She had 3,700 gallons of fuel aboard.

Great Britain several weeks ago had asked as a favor that the Air Force send the Skymaster there to make demonstration flights for Royal Air Force technicians. Thereupon, according to an official announcement, the Air Force decided to make the transatlantic flight itself without human control, if possible.

The plane was rolled out at Stephenville. The pilot, Col. James M. Gillespie of Wilmington, Ohio, chief of the All-Weather Flying Division, and the other passengers climbed aboard. The Skymaster was pointed to its distant goal. Its brain was adjusted for the task. On the field someone pushed a button.

The plane taxied down the field at maximum power, became airborne, and at 800 feet the brain

Continued on Page 2, Column 3

Fig. 2 *New York Times*, **23 Sept. 1947.**

These wonders, later augmented by power boost actuators, provided for manual control for well over a half century and continue to serve on many aircraft even today.

The triumph of the tinkerer/inventors came in 1947. Figure 2 shows a news dispatch from the front page of the *New York Times* for 23 September 1947. This article describes the flight of the U.S. Air Force's All-Weather Flying Division's C-54, Robert E. Lee. This aircraft had a Sperry A-12 autopilot with approach coupler and a Bendix automatic throttle control. These were more or less state of the art at this time. It also had some fairly special-purpose IBM equipment that permitted commands to its automatic control to be stored on punched cards fed automatically. From the time that the brakes were released for takeoff from Stephenville, Newfoundland, until the landing was completed at Brize-Norton, England, the next day, no human hand touched the control. The selection of radio station, course, speed, flap setting, landing gear position, and the final application of wheel brakes were all accomplished from a program stored on punched cards. The complete automation of aircraft flight appeared to be at hand.

This era also saw the very rapid development of theory with which we are familiar today. Servoanalysis techniques as they derived from feedback amplifier design were introduced first to servomechanisms and later to aircraft. The key contributions of Nyquist,[23,24] Bode,[25,26] Nichols, Phillips (see Ref. 27), Harris,[28] Hall;[29] the stability diagrams (now called parameter spaces); Evans' root locus;[30,31] time vectors;[32,33] etc., were all developed during this period. Although they were scarcely ever applied to automatic flight control system design, the techniques were there waiting in the wings: theories in search of problems.

The problems were not long in coming. The war had seen the advent, on both sides, of the turbojet engine, and suddenly the limits of the flight envelope were enormously extended in both speed and altitude, with concomitant configuration changes involving increased wing loadings, mass distributions concentrated in long thin fuselages, aerodynamic benefits of short span, swept wings, etc. All sorts of new problems arose that were of interest both to the aircraft designer and to the flight control designer. New phenomena were even discovered: fuel slosh, rolling instability, structural instabilities influenced by automatic control, etc.[22] Fully powered hydraulic controls came into use to handle the large hinge moments of the control surfaces, and these actuators had stability difficulties of their own.[34] All of these trends were bad news for the automatic flight control system designer, who now desperately needed and wanted analytical help. People suddenly seemed to realize that melding knowledge of aircraft stability and control and instrument design with feedback control theory was essential for the betterment of aeronautics if this was to be accomplished in an expeditious way without expenditure of an excessive number of experimental flight hours fraught with extraordinary adventures for test pilots. Thus, whereas the intimate joining of control technology and vehicle dynamic analysis would no doubt have come about in any event, it was forced by the marked deficiencies in stability of the new jet aircraft and by the advent of the guided missile, where it was obviously essential to match the dynamics of the airframe and the control system from the first flight on. This is the confluence of theory and practice. One of the authors likes to date this as 1947–1948 and associate it, admittedly on a personal basis, with a remarkable airplane now little remembered.

Figure 3 shows the YB-49, which in 1948 was to be the production bomber for the U.S. Air Force Strategic Air Command. It was the last and most successful of John Northrop's great series of all-wing aircraft. In our modern jargon, it was a control-configured vehicle, and its great success as a flying machine was peculiarly dependent on many flight control system developments. Its control surfaces were moved by the first successful fully powered hydraulic actuators developed for aircraft. These were essential because of anticipated (and actual) unstable hinge moment gradients due to increasing separation over the trailing edge as stall was approached. The isolation of the surfaces and their aerodynamic forces from the pilot required the development of artificial feel systems. The airplane was also equipped with a series-installed Dutch roll damper/rudder control system in a quasi-fly-by-wire configuration, which was, as far as we know, actually the first successful stability augmentor flown in the United States.[35] (Other aircraft companies were working on similar problems at the same time.[36]) In fact, the very name stability augmentor stems from this aircraft. It was originally stability derivative augmentor, but deletion of the middle word was necessary to readily fit the title block of an installation drawing. Besides the obvious configuration aspects to maximize performance while attending to the consequent control problems via automatic control, considerable thought was given to further improvement of the landing and cruise performance by flying the aircraft with an unstable c.g. location. Analytical and experimental studies, including a flight demonstration, of stabilization of a 10% unstable aircraft with automatic control were undertaken and seriously considered for application. This was not adopted because the aircraft met requirements readily without the additional automatic system complexity. However, the important thing for our story is that this is one of the first, if not the first, examples of the marriage of the science of the theoretician with the art of the tinkerer/inventor.

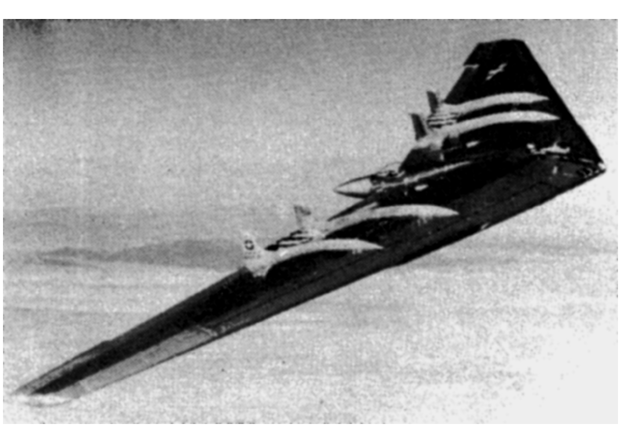

Fig. 3 YB-49 Northrop Flying Wing (Smithsonian Institution photograph A4957D).

The key feature of stability augmentation is a capacity to modify isolated stability and control features of the airframe alone in such a way that the cockpit controls are unaffected. This demands a stability augmentor actuator installation in series with the pilot's controls (or a separate control surface), which is most easily accomplished in conjunction with fully powered surface actuators. These contrast with autopilot parallel installations in which the cockpit controls reflect the autopilot servoactuators' movements. The augmentor can provide, via feedback control, any of the long desired inherent stability properties dreamed of by the early pioneers in readily specified form and in precisely measured degree provided that sufficient control power and adequate actuator performance exists. After these simple principles were understood and demonstrated for the yaw axis, other applications followed almost by analogy. Thus, in short order, in aircraft plants and autopilot companies all over the world, the yaw damper, short-period damper, roll damper, sideslip stability augmentor, longitudinal stability augmentor, transonic trim shifter, and other devices were invented, or reinvented. As shown in Table 1, these limited authority stability augmentors appeared within one generation of high-performance aircraft. These and other devices were applied with close connections between theory and practice to the alleviation of the newly encountered dynamic effects.

The other author fondly remembers the confluence of theory and practice in a systems approach to all-weather flying. Whereas the flight of the Robert E. Lee had demonstrated feasibility, reliable terminal control of jet aircraft, as in routine blind landing, for example, had yet to occur. A 1955 paper[37] reviewed the state of the art.

Figure 4[18] shows a summary of the second of our two underlying themes thus far, in some detail. On the left-hand side of Fig. 4, we have the theory of aircraft dynamics starting with Lanchester's phugoids; Bryan and his small perturbation theory; the introduction of the methods into the United States; Glauert, Bryant, Irving, Cowley, and others measuring derivatives in a wind tunnel and in full-scale flight; a confirmation of the theory of small perturbations; etc. Then, in the middle branch, we have Maxim's stabilizer, followed by a torpedo course control, then the developments of the Sperrys and some concurrent German and British developments. Finally, on the far right are the early work of Garner and Gates, and then the distinctly different conceptual developments of Nyquist and Bode in the study of feedback amplifiers. These were brought together in short form in 1950 by Bollay's Wright Brothers Lecture[38] and codified somewhat later in more extended form by the so-called Bureau of Aeronautics– (BuAer–) Northrop volumes on flight control system design, analysis, and synthesis.[34,39–44] A condensed account of the theory and systems from the extremely productive middle decade (1937–1947) of this era is given in the monograph by Hopkin and Dunn.[45]

In a more extended treatment we might have added a fourth branch to the Fig. 4 tree showing the development of flight simulation and

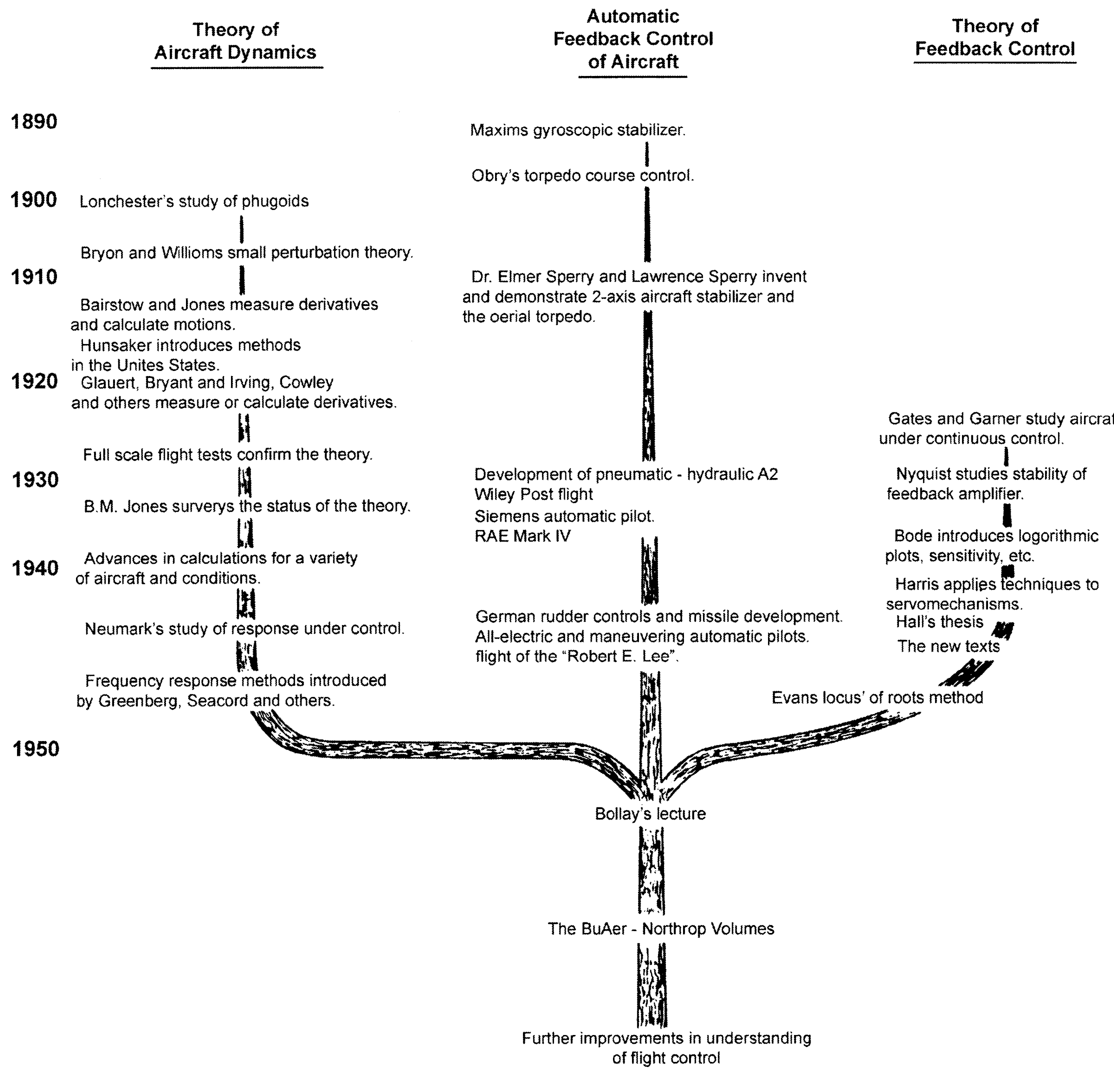

Fig. 4 Confluence of theory and practice of automatic feedback control of aircraft.[18]

associated high-speed computational tools. Begun with high-gain dc operational amplifiers, derived from late World War II fire control computers, and card programmed calculators developed from business machines, computation and simulation aids were well developed and applied by the early 1950s. Today their descendants provide us with awesome capabilities to compute, simulate, and, sometimes, to confuse.

A snapshot taken in the twilight of before yesterday might show a cadre of aeronautical control engineers confidently facing fresh challenges of requirements in defense, transportation, and the exploration of space. They had validated theories and methods including both analysis and simulation. They had models of guidance and disturbance inputs, and they had an armament of novel devices including the inertial sensors, the transistor, the printed circuit board, and the electrohydraulic valve. Also, systems had been designed and flown that incorporated a plethora of outer-loop path control functions, ranging from altitude and Mach control to optimal climb and cruise, closed around inner loops that created attitude stability, augmented damping and static stability, and suppressed or ignored the effects of higher-order structural modes.

Could anything have gone wrong? There was then a consensus perception that increasingly lengthy development times and stringent economic pressures precluded competitive prototyping of aircraft or dividing the market. This, in turn, led to the concept of concurrent development of the airframe, the engine, and the equipment including the automatic flight control system.

Murphy's law had just been enunciated in its modern version (see Ref. 46).

Only Yesterday: 1956–1981

This section might be subtitled "Quest for Safety and Reliability." It tells of the search for reliability and indifference to failure in the hardware and software and in the management of their development. A story of flight control in this era takes us from single-string analog to massively redundant digital. To exemplify the trends, we take as representative the automatic interceptor, the development of fly-by-wire (FBW) flight control systems (FCS), category 3 landing of jet transports, and the lifting reentry of reusable spacecraft.

Automatic Interceptor

At the dawn of the only yesterday era, manned bombers or cruise missiles were perceived as a threat, and the nation's shield was conceived to be a manned supersonic semiautomatic interceptor. At the heart of the defense was control surface tie-in (CSTI), creating an automatic airborne radar-controlled lead collision course for delivery of rockets and air-to-air missiles.

A very early Weapon System Project Office was set up by the U.S. Air Force to manage the concurrent development of the airplane and its avionics for what was, at one time, called the 1954 Interceptor. A number of unusual or unexpected results occurred throughout the program. Not the least was that the development of the avionics (including the automatic control system) anticipated the airplane. The 1954 Interceptor became the XF-102. It could not go supersonic in level flight. Helped by unforecasted technology, namely, the area rule, the XF-102 became the F-102A ($M = 1.25$) and ultimately the F-106A ($M > 2$). Actual CSTI was demonstrated quite late in this development cycle.

The F-106A system and its contemporaries in fighters, bombers, and first-generation jet transports were single string and analog. They were all designed using sophisticated combinations of control theory and simulation. In the course of these developments, many systems problems were uncovered and solved, sometimes more than once.[47,48] After the bugs were eliminated, the systems almost all worked well as long as they were working at all. However, they were complex, and their reliability left much to be desired. Both technology, via the transistor and printed circuit, and the evolving theory and practice of reliability engineering,[49,50] had much to offer.

The lead was taken with stability augmentors, which intrinsically require full-time operation. Because augmentors operate in series with the pilot's inputs, safety rather than reliability is paramount, especially with hard-over failures. To this end, the early single-thread augmentors were restricted in authority. As the desire for other than simple damping functions became more prevalent, a larger proportion of the total surface authority was required. To satisfy the safety requirements dual channels were used, for example, in the A3J Vigilante, with the actuators summing their forces at a common point. In the event of a hard-over failure in one channel, the other would resist and counter. Thus, the system would be fail soft (FS) rather than hard over. Conflicts between the channels were announced to the pilot, who was then confronted with the need to control the unaugmented aircraft, albeit without any control surface offset due to a hard-over failure. Unfortunately, these dual systems contained in their fundamental structure a tendency to exhibit a hypochondriac syndrome. They signaled a conflict whenever a channel-comparison threshold was exceeded (whether or not either channel had actually failed), but could give little guidance about what to do except to disengage. Furthermore, a failure changed the aircraft dynamics back to the unfavorable characteristics that the augmentation system was originally introduced to correct. Finally, the reliability was reduced because of the additional complexity introduced by the second channel. Clearly the single FS feature provided by dual-channel configurations could only be an interim step applicable only to aircraft that had some measure of manual control when unaugmented.

Early FBW Flight Control

As aircraft design sophistication and mission requirements advanced, the definition of aircraft performance optimization broadened with the times. Such features as flight on the extreme backside of the thrust required curve, stealth, supermaneuverability, short takeoff and landing (STOL) and vertical takeoff and landing (VTOL), etc., joined the more conventional performance envelope as characteristics that should be optimized. To satisfy such different varieties of optimized aircraft performance, the role of stability augmentation was changed from simple damping and coordination functions to cover a much broader scope. The design vision was essentially to separate airframe performance factors from aircraft stability and control considerations in aircraft configuration compromises. The configuration imperative to provide adequate control power remained, but within this basic constraint, stability augmentation was charged with redressing any deficiencies that may have arisen in the process. This fundamentally requires full-authority, series-type stability and control augmentation that is indifferent to failures in the system. The answer intrinsically requires redundant channels, configured to manage failures seamlessly and thereby to provide safety in exchange for complexity and the cost of more failures and maintenance actions. The achievement of full-authority, fail-operational (FO) stability augmentation was accomplished in several stages over a period of years. The most rudimentary FBW primary FCS also requires full-authority, FO channels. Because the operational requirements and required technologies for large authority stability augmentation are identical to or closely parallel those for FBW control, the evolutionary developments for both were intrinsically inseparable.

It should be no surprise that the vision of electrically signaled manual flight controls (primary controls FBW) was present in antiquity. For example, there are Wright Field memoranda from the 1930s that proposed FBW experiments. Also, there are ancient patents (going back to Maxim, with Sperry and European equivalents), in which the pilot controls the aircraft via a direct autopilot connection. The Minneapolis–Honeywell C-1A autopilot of World War II allowed the bombardier to control the aircraft in this way, as well as providing a connection with a formation stick. This was followed about 1949 or so by the U.S. Air Force All-Weather Flying Division's control stick steering projects for primary control via the autopilot. Also FBW was intrinsic to many unmanned aircraft experiments and actual operational systems, for example, target drones, during WW II and ever since. All of these provided an essential prelude to later developments.

Because the notion of FBW for aircraft manual control systems is so very old, and many partial and experimental systems were actually flown, it is quite surprising that it took so long to mature. However, as emphasized earlier, the key issue for electrical/electronic primary flight controls for manned aircraft has been safety and operability in the presence of component failures. Just as with full-authority stability augmentation, this amounts practically to providing a level of redundancy in the control channels that assures complete operability in the presence of several independent failures. The challenges to replace mature mechanical/hydraulic/electromechanical primary flight control and stability augmentation systems with FBW were mind boggling in their details, but a steady evolution in various technologies finally made these systems practical and highly advantageous for many applications. Perhaps the greatest merit has been to deliver on the promise to change the context of stability and control and aircraft configuration optimization by permitting many of the desirable stability and control features to be incorporated via the control system rather than by physical aircraft structural features.

It is fair to say that almost every aircraft prime contractor and automatic FCS manufacturer became involved to some extent or other with key FBW developments. On the research and applied development side, the U.S. Air Force Flight Dynamics Laboratory (AFFDL) and the U.S. Naval Air Systems Command played major roles, both directly and in support. At the core was an extensive search for schemes that would assure adequate redundancy levels, particularly at the surface actuation end. Several aircraft companies and the AFFDL made great advances in this connection. Without making any claims of priority or exclusivity, a somewhat random cross section of early developments might include the following examples. Northrop Aircraft, Inc., in 1952 began the development of Uniflight, a unified FCS for the F-89F, an aircraft that never came to pass, that addressed many of the integration issues, for example, combining the functions of primary flight controls, stability augmentation, and automatic pilot, multifunction surface actuators, etc. In the same general era, North American Aviation did excellent work on both the RA-5C and the XF-107 on redundant series actuation systems. These early systems were mixed FBW and mechanical systems, and a mechanical backup was always available. The ones that got into production, for example, the RA-5C, received mixed reviews. Other useful efforts were enabled by Wright Field-sponsored and in-house research, particularly in actuation and overall systems. Actuator system designs demonstrating the integration of primary control surface, (series) stability augmentation, and (parallel) autopilot actuation functions into FO packages were major contributions from AFFDL in-house research.[51] Many of the prime contractors for high-performance manned aircraft also developed multifunction surface actuation systems. Sperry, Honeywell, General Electric, Autonetics, General Dynamics, Bendix, Smiths, Elliotts, etc., explored, developed, and tested a wide range of the voting, failure detection and management, self-checking, etc., schemes required for a multi-redundant, FO system.[52] These all contributed in preparing the technology needed for application.

The next stage was the achievement of full-authority FO stability augmentation. These require at least three independent channels with some voting scheme. The redundancy is intended to manage failures seamlessly, thereby providing safety in exchange for complexity and the cost of more failures and maintenance actions. Essentially, every high-performance aircraft manufacturer developed versions of such systems. Notable early examples in the United States are the YF-107 and the F-111 triple-redundant, large-authority stability and command augmentation systems. As primary manual controls, these systems were still hybrids, retaining a level of mechanical/hydraulic backup controls in case the electronics faltered.

Category 3 Automatic Landing

A parallel branch point was the development of modes in full-authority automatic FCS (AFCS) that also require FO capability. These AFCS are in parallel with, and hence move, the pilot's controls. The initial motivation and most important early examples are systems that had to operate for relatively short times, as with autoland. There were also mission circumstances where the autopilot's actions required close pilot attention and potentially immediate take over, as with automatic terrain following. Because the AFCS was in parallel with the primary manual control, the pilot could take over in emergencies. A minimum redundancy level was thus needed to guard against hard-over failures and provide short-term continuation of operations. The Elliotts's duplicate self-monitored autopilot for the Vickers–Armstrong VC-10 was an early version launched in the 1960s.

This system provided a single-failure survival capability. The self-monitored autopilots possessed cross connections for signal consolidation (to reduce tolerance buildup) and cross comparison (for failure detection). One of the later dual-monitored autopilots controls the Concorde.

The next step, taken at about the same time as that for the VC-10, was the employment of triple and quadruple redundancy to achieve an FO capability for relatively short-time tasks, such as autoland. Priority in the development of a FCS triplex configuration is ordinarily given to Smiths and De Havilland for the Trident.

Near the end of the only yesterday era the most advanced FCS for military and airline applications remained analog, although multiple redundant where this may have seemed required. Perhaps representative of the concurrent development of this generation of aircraft and their control systems in the United States is the quadruplicated category 3 automatic landing system of the L-1011 Tri-Star. This was certified by the Federal Aviation Administration, together with the airplane. It entered airline service in the middle of 1972.

Maturation of Full-Authority FO FBW

A penultimate FBW FCS evolutionary step was full authority, FO, FBW as primary controls. Here the key step is throwing away all mechanical connections from the pilot to the control effectors. The AVRO CF-105 Arrow was an early aeronautical contender (first flight in 1957), although it was canceled before entering service and was primarily a monitored dual-channel approach. This was consistent with the then-extant mechanical/hydraulic primary controls that were also dual. (No single failure could cause the loss of the aircraft, and crew escape procedures were available.) The Apollo Lunar Module, operational in 1969, was an early space side contender. After several major starts on programs that were canceled before reaching maturity, for example, the Dynasoar, the U.S. Air Force's prototype development program initiated by David Packard offered an opportunity to work outside the box. Without a commitment to production aircraft, the introduction of new technology with only modest risk could be justified. This led to the YF-16 Lightweight Fighter Prototype with a FBW system. This and its descendents in the F-16 were the first FBW systems for modern fighters in service.[53] The early F-16 systems were analog systems with redundancy levels as high as quadruple and failure protection levels as high as two FO/fail safe based on a quadruple-redundant flight control computer. The YF-16 system flew in the early 1970s, and its improved descendents are with us today.

Expansion of Functions

The minimum equipment and system architecture required for FBW stability and command augmentation systems provide a base level that can serve as a foundation for adding many other functions with relative ease. Thus, the F-16 system incorporated full-flight envelope limiting and stretching functions that permit aggressive pilot activity to the very edges of the performance boundaries. This was just the start, inasmuch as subsequent developments of FO systems have been accompanied by major expansions in the activities demanded of flight control.

These include a cornucopia of functions intended to permit extensions in performance envelopes, longitudinal and lateral stability enhancement, span load modification, elastic mode suppression, ride smoothing, flutter prevention, etc., grouped under the general heading of active controls.[54–58] These are control solutions to airframe problems that are normally handled structurally and/or by envelope restrictions, so that active controls require a closer than ever interdependence between airframe and controller. FO controllers also permit more elaborate and varied flight-phase-dependent airframe-controller configurations in which the effective aircraft dynamics are tailored to the peculiar needs of a particular mission phase.

Technological Replacement: Digital for Analog

The last major technological advance in FBW FCS has been the general replacement of analog systems by digital versions. Many of the basic ideas, advantages, and tradeoffs were established in the late 1950s by Autonetics for the Minuteman missile integrated guidance and control system. This system was single-thread. Several generations intrude between Minuteman and now.[57,59,60] Apollo on the space side and several U.S. Air Force and NASA research and development flight efforts, including the long-running NASA Dryden Flight Research Center F-8 digital FBW experimental series,[60] played significant roles in developing the technology. Even more important, these and kindred efforts served to heighten user confidence. The most recent descendents are enormously capable, massively redundant, and contain many more modes of operation. Examples include integrated guidance, control, and flight management systems on the F-18, F-117, F-22, and the space shuttle orbiter.

Although the first flight (STS-1) of the space shuttle *Columbia* 12–14 April 1981 was an early entry on this list, the integrated navigation, guidance, and control system for the space shuttle orbiter exhibited a capability and enormously expanded scope that left predecessor FCS far behind. The reentry, approach, and landing navigation, guidance, and control subsystem of the shuttle vehicle covers a uniquely wide performance regime, and for this reason, we will take the automatic flight control of the reentry glider (Fig. 5) as a basis for discussion.

On the space shuttle orbiter, not the least difficulty is the definition of what the flight control comprises. The designation AFCS might be applied to only a handful of not very exotic sensors. Vehicle attitude angles, for example, are determined from redundant inertial platforms that also perform guidance operations. The reaction control effectors and integrated hydraulic surface actuators are naturally shared by the manual and automatic control system. The "control laws," failure detection, and redundancy management functions are implemented in software for redundant general-purpose computers, which also serve guidance, navigation, and other functions. The composite navigation, guidance, and control system is a highly interconnected and interactive entity. Neither the software nor the computer hardware is under the final jurisdiction of a FCS designer. Indeed, the morphology of the design decision tree is, to say the least, convoluted, and the design is inherently accomplished by a

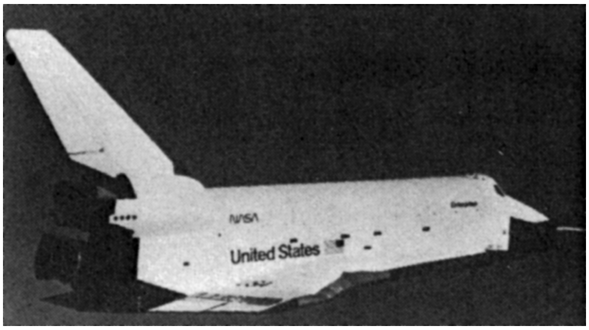

Fig. 5 Space shuttle orbiter (NASA photograph).

committee. Nonetheless, from our point of view, the most interesting problem of the space shuttle is balancing and steering from retrofiring to final approach. Therefore, although we have progressed from tethered glider to hypersonic glider, we are still confronted by the same problem as the Wrights were. However, now it ranges from hypersonic to subsonic speeds, and its solution inherently requires systems which, in all their details, are beyond the ken of a single mind.

Since Yesterday

Expansion into Commercial FBW

As with many new technologies the initial advocates of FBW control for commercial aircraft trumpeted an entire new universe of advantages, some that ultimately emerged as true marvels, and others that can be described, at best, as ephemeral. Just as with high-performance military aircraft, not the least perceived advantage was novelty in a context of highly competitive pressures. These factors, leavened with decades of FBW research and applications to military and space applications, together with commercial industry experience on the autoland systems on the British VC-10 and Trident of the 1960s and the American jumbos (L-1011, B-747, and DC-10) of the 1970s, helped to build senior management support for all-out dedication to FBW on new commercial aircraft.

At The Boeing Company commercial aircraft FBW started with spoiler flight control surfaces on the 757 and 767 (personal communication, R. Bleeg and J. McWha, 2001). These comprised triplex analog circuits (two active with the third in standby role for each control panel). Unlike the more exotic advantages cited as reasons for FBW, the major considerations in selection were time and effort savings involved with installation, rigging, and maintenance. When compared with conventional mechanical systems, functionality improvements were relatively minor, whereas weight and recurring cost savings were probably a wash. This system was certified in 1982. Such humble beginnings led to full-fledged FBW on the Boeing 777, certified in 1995[61] (also personal communication, R. Bleeg and J. McWha, 2001). No doubt the earlier successful introduction into commercial service of full time FBW on the Airbus A320 (certified in 1988)[62] and subsequent Airbus airplanes had a useful competitive effect.

The experience of over a decade of large-scale operations with FBW commercial transports has been instructive in separating hyperbole from actual promise. The features of enhanced flight characteristics, improved ride qualities, special control tailoring to maximize aerodynamic performance, and eased maintenance have now all been demonstrated. When contrasted with more or less equivalent mechanical control, the facilitation of maintenance has been a real winner. As a typical example, the 777 FBW system detects almost all its own failures, displays maintenance messages, indicates which line-replaceable unit is most likely at fault, provides and performs retest actions to reset faults, etc.[61] (also Bleeg and McWha, personal communication).

These generally favorable experiences with FBW in commercial transports assure that this technology will, in general, be sustained for the immediate future. There are, however, significant differences between the Airbus and Boeing design philosophies. The most apparent to pilots are the flight deck inceptors. The Boeing system provides coupling between pilot and copilot controllers, as well as the autopilot backdrive features of previous aircraft. The Airbus side sticks are not coupled to each other and are not backdriven to reflect autopilot operation. Similarly, the Airbus throttle levers are not backdriven to reflect autothrottle action. There are also differences at the surface actuation level. Boeing retains the full-time operation of multiple primary control surface actuators whenever hydraulic power is available, in contrast to the Airbus approach using an active-standby redundancy management configuration. Consequently, we can expect future systems to take into account experiences gained from these and other differences to provide even further positive benefits.

Flying Qualities

As manned flight enters its second century, the versatility demanded of FCS needed to meet mission requirements has made them even more important than they were at the beginning 100 years ago. The extensive innovations and operational experience since the digital dawn have made clear the great advantages of digital FBW stability augmentation systems for all manner of aircraft. The enabler has been the perfection of dual- or higher level FO multiple redundant channels coupled with extensive failure and redundancy management functions that are completely practical and safe. They have finally made manifest the holy grail payoff: the long-sought freedom to separate aircraft performance configuration considerations from pilot-centered flying qualities stability and control issues. This very freedom raises the following question: Just what should the effective aircraft dynamics be to optimize the flying qualities? This is a very complex issue because the pilot interacts with the aircraft in several different ways at different times to modulate the pilot–aircraft system behavior appropriately. Pilot actions can range from an essentially open-loop programmed controller to participation as a high-gain, highly interactive controller element in a closed-loop pilot–aircraft system. The tasks of understanding, developing, specifying, and satisfying flying qualities requirements has been a major thrust in aircraft stability and control research and design efforts from the Wrights onward.[22,63] With the advent of stability augmentation, a primary focus of flying qualities research has been to address the requirements that command and stability augmentation systems should satisfy. Extensive experiments have been conducted in fixed and moving base simulators and variable stability aircraft in endeavors to explore these requirements. Research to improve understanding of subjective assessments by pilots and to provide analytical foundations also spawned experiments and models studying human pilot dynamic behavior and human–machine control theory. These experiments and research studies comprised an interactive and iterative amalgam of theory and experiment. Some of the results of these efforts were central drivers for the command and stability augmentation developments that make up our story. In fact, for the last half-century, these studies have been addressed in close parallel and coordination with the FCS developments reviewed here, and they could constitute an additional parallel branch for Fig. 4. However, they are too extensive to fit within our current scope. The interested reader can gain a reasonable comprehension of the field by starting with Vincenti's elegant review[63] for the early developments followed by several reviews[64–66] and specifications that summarize later efforts.

Whereas we recognize that flying qualities in general is beyond the scope of this paper, there are two specific cases of closely coupled flying qualities/FCS interactions that should be mentioned. The first is the reduction to practice of the enduring concept that the FCS can be optimized for specific flight control tasks. This was initially done by adding special channels to the FCS that operated only at particular times. Such ancient equipment as the C-1A autopilot, operated under control of the bombardier during a bomb run, is a case in point. Other early examples are the addition of approach power compensators that allow the pilot to control and land carrier aircraft flying far on the backside of the thrust-required curve and the attitude stabilization equipment essential for extended helicopter hovering while dipping sonobuoys. The engagement of such apparatus at various specific times created a task-tailored FCS. The flexibility and elaboration possibilities provided by mature digital FBW FCS enable all manner of task tailoring. For example, the development and articulation of helicopter flying quality requirements pertinent to different tasks has permitted this flexibility to be fully exploited for current military helicopters.[67] Thus, rate command/attitude hold, attitude command/attitude hold, translational velocity command/attitude hold, etc., systems have now come to the fore. Task tailoring akin to these also receives attention for special situations in fixed-wing aircraft, particularly for V/STOL and carrier approach operations.

Aircraft Pilot Coupling

The second flying qualities/ FBW FCS interaction of interest is not so benign. So-called pilot-induced oscillations (PIO) or aircraft pilot coupling phenomena, where the aircraft alone may be stable but the closed-loop system comprising the pilot and the augmented aircraft is not, have been part of aviation lore from the beginning. These awkward at best and catastrophic at worst oscillatory situations can occur when the pilot is behaving as a very high-gain controller within the closed-loop pilot–aircraft system. They are invariably unexpected, very low-probability events that are fundamentally akin to oscillatory instabilities in inanimate feedback control systems. Although the cure for a particular PIO event when adequate airspace is available is for the pilot to get out of the control loop and let the stable aircraft recover, this procedure may not be pertinent when in extreme conditions, for example, close to the ground. It is a curiosity that almost all digital FBW (DFBW) FCS have encountered PIO at some stage of their development process that required special remediation. On the earlier systems, for example, the space shuttle orbiter, the PIOs could be associated with the presence of excessive effective time delays in the effective aircraft dynamics coupled with a severe flight scenario, for example, first landing on a runway and no power available for go-around, that triggered very high-gain closed-loop piloting. These phenomena, including the impact of delays due to actuator rate limiting, are well understood, but require special attention in the design process.[68,69]

Other Issues

Whereas FBW FCS are now well appreciated by aircraft designers and manufacturers, they do exhibit some features that present some major challenges. These start with the costs in hardware, software, and engineering development. On most systems, the control laws that establish the effective vehicle dynamics use only a very minor portion of the computational capacity when compared with the redundancy, failure, and system health management and maintenance functions. The verification and validation of the software for such complex systems is accomplished only at very great cost. Other downstream problems for digital flight control have yet to be totally established. For example, there appears to be a fundamental incompatibility between aircraft and FBW system lifetimes. Aircraft lifetimes are now measured in decades, whereas software engineering and hardware advances are changing in octades or even faster. Given the relatively small AFCS market contrasted to the immense commercial market for hardware, there seems to be no maximally effective way to maintain AFCS systems near the state of the art. Just how to replace computer equipment years after the original design without having to revalidate the software can be a ticklish issue.

In spite of such difficulties, real and imagined, the enormous advantages of digital mechanizations make such systems absolutely essential for the foreseeable future. In fact, with the extension of DFBW to just about every high-performance or high-technology aircraft, from now on we can conclude that FCS evolution has reached what will be a saddle point of maturity. The question is, for how long? The future is certainly clouded: Progress will not stop, but the next quantum jump is difficult to foresee. Experience has made clear that the great advantages of FO digital systems is not confined to flight control, guidance, and navigation functions. Indeed, the technology now enables complex FBW control systems that combine flight management, navigation, guidance, flight control, system health and maintenance indications, etc., with special features that can confer immunity from controlled flight into terrain, collision with other aircraft, remote control in the event of terrorist and other emergencies, etc. Requirements and preferred architectures will both advance, although in a steady stream that affects the systems primarily on the margins. While theoreticians will not be halted in their attempts to cope with the ever-expanding complexity of these metasystems, the theoretical structure for analysis and synthesis (for example, Refs. 18, 70–72) of the flight control system portions is well developed and extensively applied.

Sources of potentially wonderful opportunities (and accompanying big unknowns) that will almost certainly surface will stem from revolutionary new technologies. As a strawman extreme example, consider the potential applications to both inner- and outer-loop flight management and control using suites of global positioning system (GPS) receivers to satisfy most of the sensor requirements. When GPS signals received at appropriate locations throughout the aircraft are used at the carrier wave level, these suites can be configured to provide high-grade attitudes and attitude rate signals, as well as precision positioning. Then the functions once provided by such sensors as rate gyros, stable platforms, etc., can be accomplished within the GPS receiver suite. Furthermore, when supplemented with terrain databases and special short-range GPS ground-based transmitters, all of the functions required for automatic flight on prescribed courses relative to the Earth can, in principle, be accomplished. Whereas block diagrams showing the FCS functions and feedback essentials will parallel those of existing systems, the detailed system technological architecture would appear very different. Such GPS receiver suites could also be considered as part of an analytical redundancy scheme for FO mechanizations. Plainly, the strawman system outlined would be limited severely by GPS signal redundancy considerations for FO applications but could be suitable for situations where single-thread operation is appropriate. Other technological advances in photonics, micromechanical devices, inertial platforms on a chip, etc., will also offer fresh new approaches to solving FCS problems. It is also certain that vehicle concepts of the future will present interesting dynamic challenges that FCS will be called on to redress. Some of these ideas are already on the way to fruition; thus, revolutions are all around us. The second century of flight control will surely be full of intellectual challenges for the flight control and flight management systems engineers, with all manner of motivations for the invention of responses. It promises to be a fascinating time.

Conclusions

In spite of antecedents, many problems in automatic flight control are yet to be solved. Whereas our hardware/software capabilities have expanded enormously, the requirements are changeable and multifaceted and, often, somewhat difficult to appreciate. Whereas the theoretical structure for analysis and synthesis is well developed and practically applied in design, the actual selection of a design for a particular aircraft depends on a very large number of things that do not readily lend themselves to inclusion in, for example, a cost functional. The proper specification and satisfaction of all of these desirable characteristics in the dawning new sixth era of automatic flight control will be central because in this era the automatic control will be necessary for the successful and economic performance of some aircraft in a majority, if not all, of the flight regimes. We are faced with new challenges in which full-time, total-flight-envelope flight control promises new dimensions of both aircraft and total system performance. The shibboleths of the new flight control technology are words like multimode, full-flight envelope, decoupled, direct lift and direct side force, redundancy, graceful degradation, and other descriptive phrases adopted by the flight control salesman to describe the virtues of the products.

Perhaps an even greater challenge will stem from a fundamental paradigm shift driven by total information system integration concepts. Here the flight control, flight management, and guidance functions become immersed in a grander metasystem that encompasses all information technology purposes. The most modern flight management and control systems are harbingers of a totally integrated computational maze. Systems that exploit advanced architectures, utilizing many processors connected via appropriate communication channels with complex and situation-specific interactive pathways, comprise a megasystem that makes a flight guidance and control system difficult to trace. Understanding and appreciation for the detailed functionality of the FCS itself under all conceivable conditions will be very difficult to achieve.

To satisfy the interacting requirements and make good on the descriptive phrases requires the same kind of engineering science for the sixth era as was developed and used in the fourth. The details of the hardware and software for highly redundant and complex equipment at the fringe of the state of a particular hardware art can never be permitted to get too far from the comprehension of a generalist/analyst charged with overall system cognizance. At the same time, the vision of flight control theoreticians should never become so narrow or opaque as to provide results of only transcendental interest.

The dangers of a new separation between theory and practice are, we believe, increasing. For example, as Melvill Jones noted, two generations ago the intellectual mathematical equipment of skilled stability and FCS analysts generally exceeded their ability to perform the calculations efficiently that might be needed or desired. Nowadays, quite the opposite situation exists because advances in modeling, simulation, and computation allow the consideration of problems that at one time would have been rejected as being too time consuming. As a consequence, analysts' physical means now often exceed their mental grasps, and what could be computed may far exceed their understanding or appreciation. This can lead to an excessively empirical approach to design that is similar to the one used by the tinkerers 60 or more years ago. However, a key difference exists in the abstractions involved. Regardless of the detail and complexity of our mathematical models, they remain just that, whereas the physical equipment and the aircraft that are the objects of our abstractions were the tinkerer's models. Viewed in these terms, too great a reliance on a numerical–empirical approach to design is no better, and may even be worse, than the physical empiricism of earlier days. When inundated by computer printouts, strip chart recordings, and diverse graphical presentations, we are confronted with a crucial problem: What is the essence? What does it all mean? Even when this is unraveled, paper studies and simulations are obviously only as good as the implicit underlying assumptions. No matter how prescient the engineer may be in analytical forecast of system normal and abnormal behavior, one invariably finds a reservoir of residual problems when the system is built. Thus, in the sixth era of flight control, it is essential that we keep the tinkerer/inventor and the theoretician communicating. Concluding his 1914 lecture, Barnwell said[7]:

> In the first over-all design... no pains should be spared.... If this be done, using with due common sense every source of reliable data, and doing everything methodically and thoroughly, it is highly probable that the results will be good, and if one goes on working thus in subsequent designs, altering up empirical constants as found necessary or advisable from increasing experience, one will design better machines and *will know why they are improved*. [Emphasis added.]

Despite the enormous changes in conceptual viewpoint and technological practice that have taken place since 1914, we cannot improve on these appropriate remarks. Indeed, we happily subscribe them.

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