History of Key Technologies

AIAA 81-4166

50th Anniversary 1981

Eighty Years of Flight Control: Triumphs and Pitfalls of the Systems Approach

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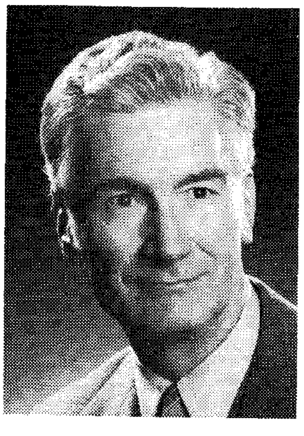
Introduction

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 eighty years 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, nor 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, 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. So, 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 automatic feedback control systems for aircraft.



Duane McRuer attended the California Institute of Technology, where he received the B.S. (1945) and M.S.E.E. (1948) degrees. Since 1957 he has been President and Technical Director of Systems Technology, Inc. Previous associations include Northrop Aircraft, Inc. (1948-54) and Control Specialists, Inc. (1954-57). His professional experience encompasses all aspects of control systems engineering, with primary emphasis on system development efforts concerned with manual and automatic flight control and guidance for manned and unmanned aerospace and land vehicles. In this connection he has played a responsible role in over 30 systems for transports, bombers, fighters, RPV's, missiles, research craft, and space vehicles. His major individual work has been in fully powered controls, vehicle stability augmentation, vehicle dynamics, flying qualities, human operator dynamics, unification and integration of manual and automatic flight controls, and optimization of vehicle characteristics from the flight control standpoint. He has published over 100 technical papers and reports on these subjects, and is coauthor of *Analysis of Nonlinear Control Systems* (Wiley, 1961; Dover, 1971); and *Aircraft Dynamics and Automatic Control* (Princeton University Press, 1973). Mr. McRuer has chaired and served on many government and professional society committees, including terms as President of the American Automatic Control Council (1972-73) and Chairman of the AIAA Technical Committee on Guidance and Control (1967-68). He has received several awards for his scientific and engineering work including the Mechanics and Control of Flight Award of the AIAA, the Franklin Institute's Louis E. Levy Gold Medal, and the HFS Alexander C. Williams Award. He is a Fellow of the AIAA, IEEE, SAE, AAAS, and HFS.

Dunstan Graham was born in Princeton, N.J. on August 17, 1922. He earned the 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 de-icing. 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. Resigning these positions in 1980, he worked as an independent consultant until his recent association with Custom Computer Consultants. He has frequently collaborated with Duane McRuer on books, papers, projects, and technical reports. A Fellow of the IEEE, Dunstan Graham is also an Associate Fellow of the AIAA and a Member of the Institute of Navigation.

Received March 24, 1980.

EDITOR'S NOTE: This manuscript was invited as a History of Key Technologies paper as part of AIAA's 50th Anniversary celebration. It is not meant to be a comprehensive survey of the field. It represents solely the authors' own recollection of events at the time and is based upon their own experiences.

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, 1-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	(Emphasis on flying qualities and task-specific modes)						(Empnasis on economics)

While 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 feedback signals, that is, his attitude with respect to the ground, his position with respect to a desired landing point, etc., should be able to operate the controls so as 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 if only the pilot were provided with sufficiently powerful controls with which to balance and steer—in other words, 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 aileron *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, e.g., to run gyro wheels. By the late 1940's the technology was all electric, from sensors to servos, with carrier circuits at intermediate stages. In the early 1950's dc operational amplifiers and electrohydraulic servo actuators became prominent, especially with stability augmentors. Transistors followed tubes and magnetic amplifiers until, at present, the signal circuit technology is solid state, analog and/or digital, with fiber optics beginning to enter the field. 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 depicted in Table 1, although no claim is made for completeness. The time lines relating when particular system functions could be effected by feasible physical means (Table 1) form one of our underlying historical themes to which we shall refer from time to time.

A Choice of Eras

Our history of flight control as an often cyclic evolution of challenge, response, ingenuity, and learning may be divided conveniently into four eras. These of course have been arbitrarily and discriminatorily chosen with forethought. From earliest times to 1901 is the "Early Dawn." The epoch from 1901 to approximately 1931 was a "Classical Age," the heritage of the Wright Brothers. Then from 1931 to 1956 was "Before Yesterday" while from 1956 to 1981 was "Only Yesterday." (We borrow here the evocative phrases of Frederick Lewis Allen, editor and social historian.)

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 R. W. Howard.[1]

The Early Dawn: Earliest Times to 1901

The early dawn ages were characterized by a record of relatively rare individuals who contemplated dynamical aircraft stability and flight control. In a previous paper[2] we have pointed to the contributions of Lanchester (1897) and Maxim[3] (1891). Inspired by Maxwell (1868),[4] Routh (1877) in his "Stability of a Given State of Motion"[5] had provided a theoretical background for "inherent" stability, but for a long time his work was unremarked except possibly by transcendental mathematicians.

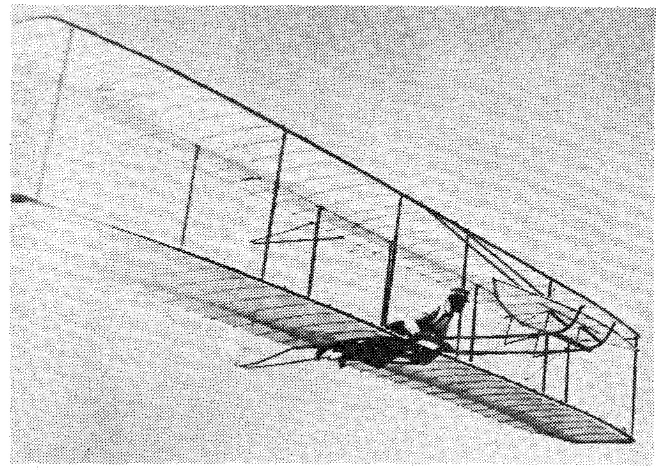


Fig. 1 1902 Wright glider (Smithsonian Institution photo A42413-E).

A Classical Age: 1901-1931

By the end of year 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 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.

Up until about 1931 any triumphs of aviation, including the use of the airplane during the Great War and the early development of air transportation, were achieved with manual control and certainly without the use of "higher" mathematics. They were the heritage of Wilbur and Orville Wright.

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 F.S. Barnwell very early in the fateful year 1914.[7]

During this Classical Era two types of engineers were active—the dynamic theoreticians and the tinkerer/inventors. They were busy, and ultimately productive. But because of the emphasis on, and availability of solutions for, adequate *manual* control, there was no readily perceptible requirement for their efforts.

The Scientists/Theoreticians

In the year of the first flight we have the first major contribution of the pioneer theoretician, G.H. Bryan.[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.[10] In the period from about 1910 through the early 1930's there was an enormously productive effort in Great Britain. People calculated the stability of aircraft, calculated the response to disturbances, calculated the response to 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] He stressed that good stability was not enough, that it was essential also to consider the amplitudes of the several modes of motion. In 1926 Garner made an analysis of the lateral-directional motions of an airplane under the influence of feedback control.[12] 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 RAE (Royal Aircraft Establishment) automatic rudder control which 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-order lag.[13]

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.[14] They crossed the lines by describing both the practical and theoretical aspects of autopilot development.

By 1935 when B. Melvill Jones surveyed stability and control,[15] the classical approach initiated by Bryan 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 F.S. 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. But, Melvill Jones did not cover feedback control of the aircraft's motions although he wrote a decade after Gates' initial efforts. He recognized that:

> It is probable that mechanical control will become increasingly popular for large long-distance aeroplanes, 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 mehanical control." Melvill Jones' comment on the application of the theory which he did cover, i.e., aircraft-alone dynamics, was:

> 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 aeroplanes 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 aeroplanes from making use of the methods. . . .

We shall refer again to this quotation. But it does, by extension, make matters clear about automatic flight as well. Since the procedures then available for treating automatic systems involved factoring quintics or higher degree polynomials, whereas the aircraft-alone equations were only quartices, 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 ten 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.

The Tinkerer/Inventors

Beginning in 1909-10, Dr. Elmer Sperry, later assisted by his sons Laurence and Elmer A. Sperry Jr., and other associates, made a series of experiments in the control of aircraft flight using gyroscopic references. The story of the 1912-14 Sperry Airplane Stabilizer has been well told and illustrated elsewhere.[1,2,16,17]

Other inventors were also very active. Starting 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 servo mechanism drives of the control surfaces. Table 2, adapted from Haus,[18] provides a shortened survey of these extensive efforts. Perhaps a sad part of all this vast experimentation on feedback control of aircraft was that nobody had any use for it. The designers of aircraft, following such rules as those exemplified by Barnwell's book,[7] had learned how to provide enough stability so that the pilots could handle the airplane and nobody needed automatic feedback control.

But firms specializing in automatic flight control persevered and continued their efforts. Writing in 1931, Elmer Sperry Jr., described[19] 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 21⅓ days. On the morning of June 23, 1931, pilot Wiley Post and navigator Harold Gatty took off from New York in the sleek "Winnie Mae." 15,477 miles and 8 days 15 hours and 51 minutes later, Post and Gatty landed in New York again. They had been around the world via Europe, Siberia, Alaska, and Canada.

Table 2 Early flight control inventions

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

Before Yesterday: 1930's-1956

1932 saw the introduction of the Boeing 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 alone. Between the 15th and 22nd of July, 1933, he flew the "Winnie Mae" around the world in a total flying time of 115 hours, 3½ minutes. Over an almost identical route he nearly halved the elapsed time. Post gave the automatic pilot, "Mechanical Mike," credit for helping 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 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 Second World War 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 Co. 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[20] 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 which 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 aircraft themselves, 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 was still present, and cut-and-try did the job; indeed, so well that all the elements of a modern automatic pilot were now at hand.

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 September 23, 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. Servo analysis techniques as they derived from feedback amplifier design were introduced first to servomechanisms and later to aircraft. The key contributions of Nyquist,[21] Bode,[22] Nichols, Phillips,[23] Harris,[24] Hall,[25] the stability diagrams (now called parameter spaces), Evans' root locus,[26] time vectors,[27,28] 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, the 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 his new fixit man, the flight control

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*, Sept. 23, 1947.

designer. New phenomena were even discovered: fuel slosh, rolling instability, structural instabilities influenced by automatic control, etc. 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. 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! So, while 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 us likes to date this as 1947 to 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 United States 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 upon 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

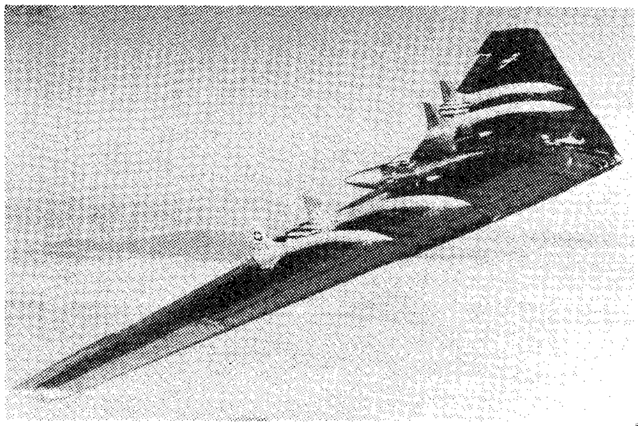


Fig. 3 The YB-49 Northrop Flying Wing (Smithsonian Institution photo A4957D).

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, the first successful stability augmentor flown in the United States.[29] (Other aircraft companies were working on similar problems at the same time.[30]) 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. But 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.

The key feature of stability augmentation is a capacity to modify isolated stability 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. 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. After these simple principles were understood and demonstrated for the yaw axis other applications followed almost by analogy. So, in short order, there was invented, or reinvented, 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. 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 new dynamic effects.

Another of us fondly remembers the confluence of theory and practice in a systems approach to all-weather flying. While the flight of the "Robert E. Lee" had demonstrated feasibility, reliable terminal control of jet aircraft, as in routine blind landing for exmple, was yet to occur. A 1955 paper[31] reviewed the state of the art.

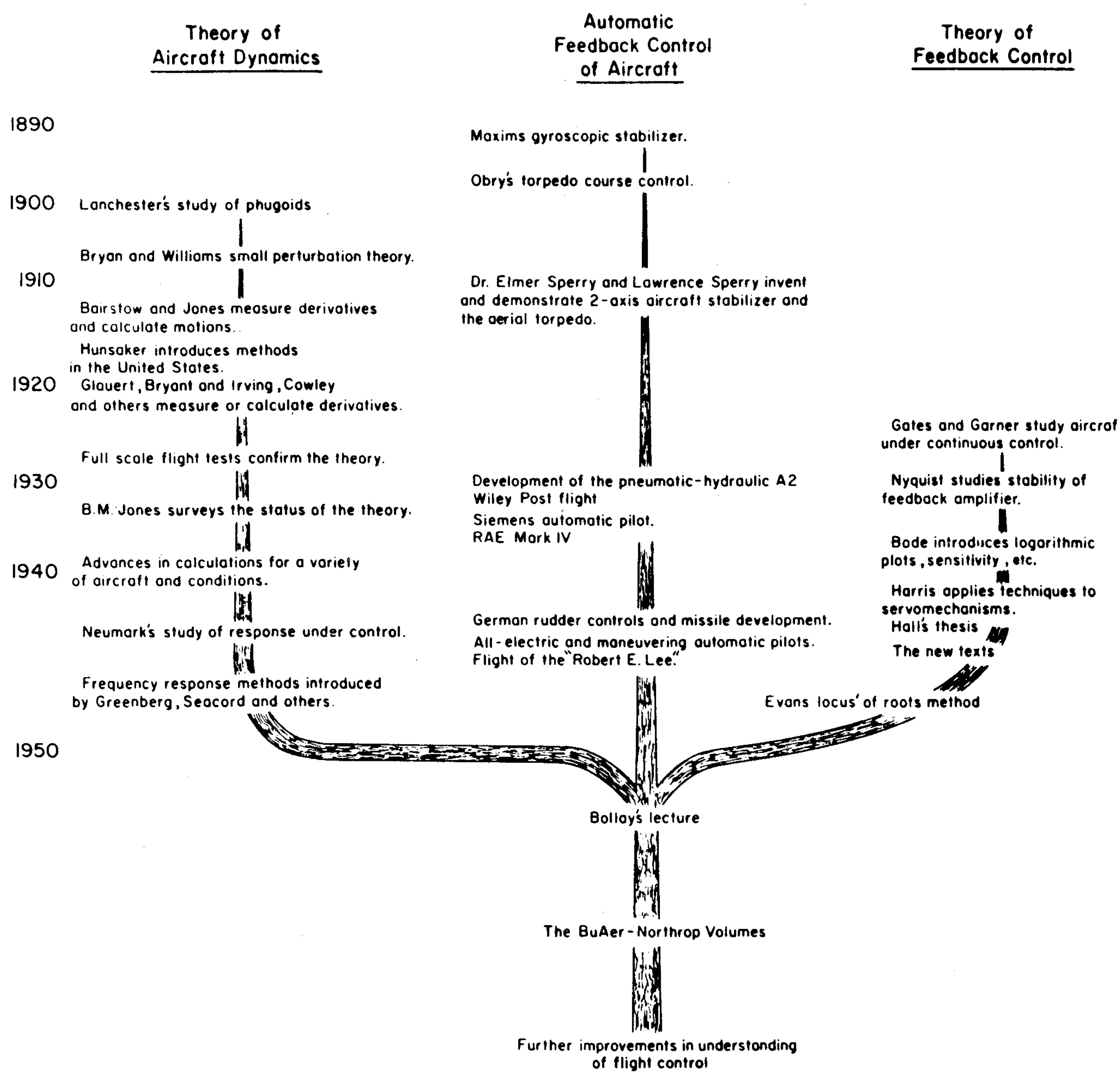


Fig. 4 Confluence of theory and practice of automatic feedback control of aircraft. [17]

Figure 4[17] summarizes the second of our two underlying themes thus far, fleshed out in some of the details. On the left-hand side of the figure 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 is 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 W. Bollay's Wright Brothers Lecture,[32] and codified somewhat later in more extended form by the so-called BuAer-Northrop volumes on flight control system design, analysis, and synthesis.[33] A condensed account of the theory and systems from the extremely productive middle decade (1937-47) of this era is given in the monograph by Hopkin and Dunn.[34]

In a more extended treatment we might have added a fourth branch to the Fig. 4 tree showing the development of flight simulation and associated high-speed computational tools. Starting 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 1950's. 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 confidentially 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 inertial sensors, the transistor, printed circuit board, and the electrohydraulic valve. Also, systems had been designed and flown which incorporated a plethora of outer-loop path control functions, ranging from altitude and Mach control to optimal climb and cruise, closed around inner loops which 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.[35]

Only Yesterday: 1956-1981

This section might be subtitled: "Quest for Reliability." It tells of the search for reliability 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. In order to exemplify the trends, we take as representative the "automatic interceptor," "Cat III" landing of jet transports, and the lifting re-entry of reusable spacecraft.

At the dawn of Only Yesterday 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" 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 (WSPO) 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 control surface tie-in 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.[36] After the bugs were eliminated, the systems almost all worked well as long as they were working at all. But, 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,[37,38] 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 hardover 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 (e.g., in the A3J Vigilante), with the actuators summing their forces at a common point. In the event of a hardover failure in one channel the other would resist and counter. Thus the system would be "fail soft" rather than hardover. The reliability was, however, reduced because of the additional complexity introduced by the second channel.

A much more elaborate version of a dual system was the Elliotts' duplicate self-monitored autopilot for the Vickers-Armstrong VC-10. This system was designed for use in automatic landing and 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 latest dual-monitored autopilots controls the Concorde.

The next step, taken at about the same time as that for the VC-10, may well have been the employment of triple and quadruple redundancy to achieve a "fail-operational" capability for relatively short-time tasks, such as autoland. Priority in the development of a flight control system triplex configuration is ordinarily given to Smiths and De Havilland for the Trident. This system has made more than 50,000 in-service automatic landings.[39]

Up to the eleventh hour of Only Yesterday the most advanced flight control systems 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 III automatic landing system of the L-1011 "Tristar." This was certified by the FAA, together with the airplane. It entered airline service in the middle of 1972.

On the military side, redundant analog systems have become operational full time. Starting with rudimentary single thread pilot command by wire in the early 1950's (e.g., the C-1A's formation stick, YB-49 rudder controller, and the All-Weather Flying Division's control stick steering), steady but very slow progress was made in redundant equipment coupling fly-by-wire control of the surface actuators with stability augmentation. Almost all of this was experimental because commitment to production aircraft appeared risky and unnecessary. After several major starts on programs that were cancelled before maturity (e.g., the Dynasoar), and successes in manned space vehicles (e.g., Apollo), the F-16 became the first in what will surely be a long series of totally integrated fly-by-wire augmentation and control systems. Such systems intrinsically incorporate full flight envelope limiting and "stretching" functions that permit aggressive pilot activity to the very edges of the performance boundaries.

The progress of technology for fail-operational systems has 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."[40-44] These are control solutions to airframe problems which are normally handled structurally and/or by envelope restrictions, so active controls require a greater than ever interdependence between airframe and controller. Fail-operational 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.

Over the last decade digital flight control systems have come to the fore. Many of the basic ideas, advantages, and tradeoffs were established in the late 1950's by Autonetics for the Minuteman missile integrated guidance and control system. This system was single-thread. Several generations intruded between Minuteman and now,[43,45] leading to most recent descendents which are massively redundant and contain many more modes of operation. Examples include integrated guidance and flight systems on the F-18 and the Space Shuttle. The re-entry, 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 re-entry glider, Fig. 5, as a basis for discussion.

On the Shuttle Orbiter, not the least difficulty is the definition of what the flight control comprises. The designation "automatic flight control system" might be applied to only a handful of not very exotic sensors. Vehicle attitude angles, for example, are determined from redundant

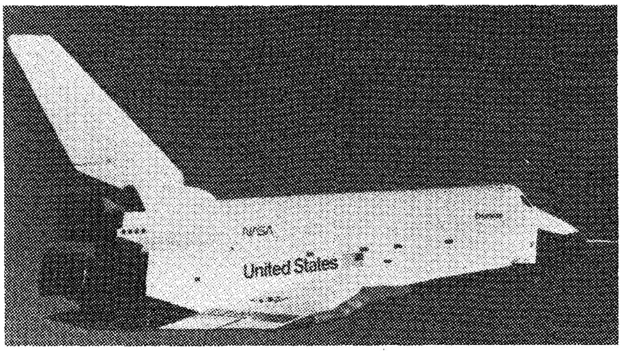


Fig. 5 The Shuttle Orbiter (NASA photo).

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 are under the final jurisdiction of a flight control system designer. Indeed, the morphology of the design decision tree is, to say the least, convoluted; and the design is inherently accomplished by a committee. Nonetheless, from our point of view, the most interesting problem of the Space Shuttle is balancing and steering from retrofire to final approach. So, although we have progressed from tethered glider to hypersonic glider, we are still confronted by the same problem as the Wrights. But, 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.

Conclusion

In spite of antecedents, many problems in automatic flight control are yet to be solved. While our hardware/software capabilities have expanded enormously, the requirements are changeable and multifaceted and, often, somewhat difficult to appreciate. While the theoretical structure 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 which do not readily lend themselves to inclusion in, for example, a cost functional. The proper specification and satisfaction of all these desirable characteristics in the dawning new fifth era of automatic flight control will be central, for 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 good words adopted by the flight control salesman to describe the virtues of his products. To satisfy the interacting requirements and make good on the descriptive phrases requires the same kind of engineering science for the fifth 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 flight control system analysts generally exceeded their ability to efficiently perform the calculations which might be needed or desired. Nowadays, quite the opposite situation exists, because advances in both analog and digital computation allow the consideration of problems which at one time would have been rejected as being too time consuming. As a consequence, the analysts' physical means now often exceed his mental grasp, and what he can compute may far exceed his understanding or appreciation. This can lead to an excessively empirical approach to design which is similar to the one used by the tinkerers thirty or more years ago. But 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 which 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 and strip chart recordings we are confronted with a crucial problem: What is the essence? What does it all mean? And even when this is unraveled, paper studies 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 apparatus is built. Thus, in the fifth era of flight control, it is essential that we keep the tinkerer/inventor and the theoretician communicating.

Concluding his 1914 lecture, Barnwell said:

> 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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