Automatic flight controls in fixed wing aircraft
The first 100 years

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1. INTRODUCTION
In 1973, automatic flight controls is one of the most exciting fields of technology, requiring a balanced combination of art, science and human understanding, and the efforts of large project management teams backed up by adequate resources to bring any new concept to fruition.

Today's systems derive almost entirely from the technology of the past 25 years, and hence it is little known that there was some activity in automatic flight control for fixed wing aircraft as long ago as 1873, some 30 years before the world-changing events at Kittyhawk and when mechanical flight was still confined to balloons and a few rudimentary gliders.

One century ago was still the era of lone inventors, rather than project management teams. It was a time when exceptional engineers and scientists could obtain a significant outcome from their own thinking and personal skills. It was a period when the world had just been given, largely as a result of the efforts of individuals, the telephone, typewriter and torpedo.

However, automatic controls engineering, like "mechanical flight" was in its infancy. To most people, problems of control and stability were confined to such things as maintaining upright and in steady motion on a penny farthing bicycle. The most widely used control device was the steam engine speed governor. Gyroscopes had a recognised potential, but were, as yet, little more than scientific curiosities. Negative feedback had been known for 2000 years, but was little understood. Mathematical analysis was to some extent pursued for its own sake, and was little used by the great creative engineers like Edison. Indeed it was to be some 70 years before the work of the French mathematician Laplace was applied to the analysis of the stability of systems in such a manner that it became the everyday language of the controls engineer.

The centenaries of man's endeavours in many fields of science and engineering are rolling by and 1973 now marks 100 years of background on automatic flight controls for fixed wing aircraft.

It is the object of this paper to trace the evolution of the systems involved, concentrating mainly on the period from the beginning up to the end of the Second World War.

The last twenty-five years has seen vast activity on a very wide front which has been well documented. However, to give some perspective to the earlier work, some aspects of this recent history are covered, but these are restricted to topics of particular significance such as the impact of available technology, the development of the current generation of automatic landing systems and the first commercial supersonic system.

The original paper was presented to a joint meeting of the Royal Aeronautical Society and Institute of Electrical Engineers at 4 Hamilton Place on 18th October 1972.

Steeding Wings
(Musee de l'Air, Paris)

Figure 1. Renard Decaplane model.

2. EARLY HISTORY
In 1873, the Frenchman, Colonel Charles Renard tested from the St-Eloi Tower near Arras an unmanned multiwing glider (decaplane) incorporating an automatic control device aimed at improving the machine's directional stability (Fig. 1).

The automatic device comprised a transverse pendulum connected to operate differentially a pair of small rotatable wings. Colonel Renard's idea was that "if the aircraft leaned to one side at the beginning of a turn, the action of these small wings, one rising inside the turn and the other descending on the outside of the turn, would straighten the aircraft". Renard's machine was possibly the first on which an attempt was made to use an active stability device or 'artificial stabiliser' and he was not to know that it was the forerunner of a range of similar devices and the first contribution to a new field of technology.

In fact the decaplane test was unsuccessful. It descended from the tower in a spiral dive and although the stabilising wings appeared to operate as expected, they were clearly unable to counteract the effect of the powerful lateral instability which was inherent in the design. (There appears to be an error on all ten wings.)

Today, Renard is considered by historians to have made his major contribution to aeronautics in the field of
airships, and although his joint effort with Krebs to produce the first navigable airship "La France" was a significant milestone in aviation history, it is to be hoped that it succeeded in lifting. Unfortunately it fouled the guard upon the assumption that machines should be sufficiently resistant to any disturbance to be able to maintain their flight path without the need for any significant intervention by the airman-pilot. The early inventors hoped to achieve this by designing their machines with the characteristics of high pendulosity, which they called at the time "high stability". They considered this "stability" as a single entity, and it is quite likely that most were unaware of the separate elements of dynamic and static stability from their observations of the very short duration, slow speed flights of their manned gliders, or their unmanned models. Indeed it was not until 1911 that Professor Bryan first analysed the equations of motion of the six degrees of freedom of an uncontrolled aeroplane, derived the concept of longitudinal and lateral flight dynamics, and expanded the concept of stability into an analogous domain with various well known stability roots. The early experimenters had only early concept of safety altitude. In addition, before the turn of the century, they concentrated mainly on straight and level flight and did not predict that the airman-pilot would subsequently play a very active part in control, especially in roll, and they underestimated structural requirements which would result from his capability to control the machine. Thus the main efforts were directed towards the achievement of "high stability" to external disturbance, and the view was generally held that aircrews would steer their machines on the same manner as a helmsman would steer a ship, and that little skill or effort would be required. This view was supported by the experimental work of the Wright Brothers in 1905 while being done at the time, notably by the German experimenter Lilienthal in his early flights. Lilienthal was the first in the pursuit of a solution to the "stability" problem received as much attention, if not more, than the prime ones of getting adequate engines and flying machines. There were two main schools of thought as to how the so called high degree of "stability" could be achieved. One held that it could be made inherent in the basic design of the craft, on the lines of Cayley's concepts, while the other school argued that automatic control means would have to be furnished, akin to, as Lancaster later said, "the brain and nerve centres of birds". In 1891, according to a patent in his name, the experimenter Airman invent Sir Hiram Maxim gave serious consideration to the "artificial" approach. He described his steam powered aeroplane using pendulous gyroscopic stabilization in pitch, the autopilot. This, he intended that the stabiliser should enable his machine to be held at a constant climb angle as set into the control wheel. Unfortunately he then goes on to reveal that at the time his knowledge of flight dynamics near the stall was fallacious. He assumed that in the event of engine stalling, the aeroplane would come menace to traffic back wards. This would reverse the pressure on the speed yoke so as to demand via the slotted arm to the mechanism of the machine in flight resulting from its own wind-glider. His aeroplane design was almost symmetrical so perhaps he thought that this yawing restraint could be introduced; in fact in 1908 he wrote that his design arranged that "the lifting effect...was directly over the centre of gravity" which opens the way for some interesting speculation. Air Hiram Maxim should rightly be credited with the invention and construction of the first practical attitude demand autopilot for aeroplanes and could be excused his early misconception about stabilising which a man of his genius would have corrected if his experiments had continued. By 1904 he had produced a full scale prototype aeroplane and that is what he intended, but he did not then have in mind to test the power/ lift and the stability/controls aspects all together. He intended that they be tested separately, which would have to be matched together. One example is his servo rotary feedback rod, which abuts onto the pilot's demand unit, comprising a very simple implementation of a mechanical (com­ monalional) control. However Maxim should rightly be credited with the invention and construction of the first practical attitude demand autopilot for aeroplanes and could be excused his early misconception about stabilising which a man of his genius would have corrected if his experiments had continued.

3. THE TURN OF THE CENTURY

Before the realisation began to dawn that the "high stability" attitude and lateral manual control for a basic design, with the wing notching, the wing warpings to be rudderless to offset "wing warp" drag and longitudinal instability, the revolution unknown to the reasonable attitude and lateral and longitudinal flight dynamics which Bryan later derived forms a formal analytical approach. It would seem that by 1905 two severe blows had been struck against much of the work of the previous two decades. First, the concept of designing for high "stability" with fixed controls which would have to be compensated for by somewhat unacceptable control was almost certainly as a result of such limitations that Lilienthal, in 1896, met his death in one of his hang-glider. The turn of the century the Wright Brothers in America had quickly followed the work of the early experimenters. Sir Hiram Maxim should rightly be credited with the invention and construction of the first practical attitude demand autopilot for aeroplanes and could be excused his early misconception about stabilising which a man of his genius would have corrected if his experiments had continued. By 1904 he had produced a full scale prototype aeroplane and that is what he intended, but he did not then have in mind to test the power/lift and the stability/controls aspects all together. He intended that they be tested separately, which would have to be matched together. One example is his servo rotary feedback rod, which abuts onto the pilot's demand unit, comprising a very simple implementation of a mechanical (commonalional) control. However Maxim should rightly be credited with the invention and construction of the first practical attitude demand autopilot for aeroplanes and could be excused his early misconception about stabilising which a man of his genius would have corrected if his experiments had continued. Second, the new concept of 'artificial' stabiliser and the stabiliser's ability of the unstable or neutral aircraft was almost certainly as a result of such limitations that Lilienthal, in 1896, met his death in one of his hang-gliders.

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"A body moving quickly through the air is liable to suffer sudden and erratic movements. It is, therefore, very difficult to cause a plane to move straightforward, and if the plane is inclined so as to cause it to rise in the air," he therefore intended that the stabiliser should enable his machine to be held at a constant climb angle, or required aircraft attitude. It would seem that by 1905 accelerometers and rate gyroscopes were being used to measure acceleration and rate of turn to provide inputs to the autopilot. However, by 1905 it will have been interesting to speculate on the future of this approach. By 1904 he had produced a full scale prototype aeroplane and that is what he intended, but he did not then have in mind to test the power/lift and the stability/controls aspects all together. He intended that they be tested separately, which would have to be matched together. One example is his servo rotary feedback rod, which abuts onto the pilot's demand unit, comprising a very simple implementation of a mechanical (commonalional) control. However Maxim should rightly be credited with the invention and construction of the first practical attitude demand autopilot for aeroplanes and could be excused his early misconception about stabilising which a man of his genius would have corrected if his experiments had continued.

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scopes for course keeping. Louis Brennan and others were
experimenting with monorail trains directly stabilized with
heavy gyroscopes. Everything pointed towards an increase
in the use of "artificial" device to gain high stability.

The most extensive flying experience was with balloons
and aeroplanes, which were relatively stable, sedate and
friendly, and heavier-than-air machines would certainly be
expected to exhibit the same characteristics. It was argued
by many that if artificial stability were desirable in ships
they would be essential in aeroplanes; perhaps more so
because "artificial" was more relative than the sea,
and aeroplane "hulls" were less developed than ships' hulls.

Pursuing the line that the common man would soon
have need for an aeroplane like the Volkswagen concept,
Stanley Rech, then aviation editor of the Scientific-
American, with some advice from Elmer Splyr, built
over the period 1908-1910 an aeroplane on the Biplane
pattern with a large engine driven gyroscopic suspended
rigidly, spins axis vertical, beneath the forward fuselage.(91
This and aeroplane "hulls" were less developed than ships'.

The pendulum was an improvement on that of Beach in
1909. This may have provided sufficient angular
momentum of the wheel being at right angles. Apparently
the delicate airframe. The use of gyroscopes in this direct
way has always presented fundamental problems due to
the disturbing moment and the resistance from the angular
momentum of the whole system. Rightly, the gyro-equipped
plane did fly, but only performed gradual movements and
must have been nearly impossible to control.

It is difficult to believe that Elmer Splyr, who was said
to have assisted Beach, and who checked his calcula-
tions, could have really supported this design, but he did
in fact publicly associate himself with this project. Splyr
understood the possibilities of similar gyroscopes very well by
this time and in 1909 had made notes about the application
of signalling gyroscopes to aeroplanes, although perhaps he
did not understand the problem fully and may have con-
sidered them capable of use as a gyro merely to give a high inertia,
which was one of the methods used to stabilise a rolling ship.

Between 1911 and 1912 in France, several inventors
made experiments on the use of gyroscopic precession for
the stabilisation of flying machines. The concept of Louis
Marmonier (lo.114) was an improvement on that of Beach in
that he combined the characteristics of a heavy engine-
driven gyroscopic (as in the pendulum type) and connected
the device with cables to "warp" the controlling
surfaces (Fig. 3). The pendulum rod was pivoted so as to
swing laterally. It had "particular emphasis should be laid on the need
for greater automatic stability in all heavier-than-air flying
machines... and that inventors should aim rather at increasing automatic stability than at increasing speed"(10) He probably had "inherent" rather than "arti-
ficial" stability in mind at the time, certainly the pro-
tagists of both schools of thought remained active and vociferous.

Although many of the artificial stability devices pro-
posed in the early years of powered flight employed gyro-
topes, there was considerable effort also expended in
misguided attempts to get attitude information from a
simple pendulum. A great deal of controversy surrounded
their use, probably fractioned by the inventor to be inde-
hent concepts of the 1890s; but all such attempts
were destined to failure due to susceptibility to unwanted
accelerations and poor damping. Some inventors undoubt-
edly used a damped pendulum to its advantage as a side
force sensor, but it was never possible for such devices
alone to solve the severe and complex problems
which the automatic stabilisation of aeroplanes posed.

A number of the early pendulum devices were coupled
with wind sensors of various types and such designs per-
sisted or a long time, which seems to indicate that they
serviced a useful purpose. They may have compensated
for early design limitations, or been effective as verifi-
cation references to some extent due to the limited manoeuvre
expansions of the early machines.

Certainly in the underpowered machines of the day
movements were fairly reluctant to perform any steeply
banked manoeuvres.

There were numerous variations on this theme, from
pendulum coupled to controls in schemes in which engine
and pilot were suspended, in underdamped, cradle, some
having appropriate connecting cables or rods to the con-
trol surfaces. One such example was the "Mareau" "Aero-
sable"(15) in which this French inventor frequently flew
without "hands on" take-off. The Mareau machine had a cradle cockpit pivoted to swing freely
and appropriately connected to the elevator and ailerons,
so that it could be controlled by deliberate movements
of the pilot. Its stability was also subject not only to applicable controls, but also to the
rotation of the cockpit area. There would also be a damping action
from the control surfaces. It was therefore not really a simple control.

The basic shortcomings of the simple pendulum oper-
ated by the gravity force was that it could not self-con-
trol the horizontal position of the body due to the lack of
any airmen to oppose the use of all arti-
ficial stability devices, while urging the automatic controls
designers to strive to do better. There is no doubt
that the problem of stability exercised the minds of
everybody in the field.

A number of skilled designers attempted to solve this
problem, apart from the Wright one already mentioned.
Budig, Escrib and Douivre were active on this in the1912-
1914 period. The Doutre Speed Maintainer(17) of 1912 is re-
presentative and is what today we would call a stick-push.
This ensures that an artificial device would be employed if a fall in speed occurred for any reason. It was
ingenious design (Fig. 6). It weighed 44 lb and was similar in effect to those where the wind vane was at right angles
to the direction of flight and normally inactive against a spring and an abutment, unless the windspeed dropped below the safe level. In
which case a pneumatic servo operated to depress the elevator.
which was indicated to the pilot by the movement of his control stick. The vane action was also dampened by spring restrained moving weights, which formed in effect a longitudinal accelerometer, but was demonstrated in a Maurice Farman biplane, piloted by M. Didier. It was not until well into the First World War that better engines and machines allowed cruise speeds to increase to the region of 100 mph which was sufficiently remote from the stall to remove the immediate interest in such protection. By 1913, all manner of aeroplanes were flying which made use of one whatever of any artificial (automatic) stabilisation devices. However, the need for pilots to be highly alert and agile was still by no means generally accepted and various ideas for improving stability (and almost significant development had commenced in New in a Maurice Farman biplane, piloted by M. Didier. The device was fully demonstrated remotely from the stall to remove the immediate interest in such a manner as to maintain its stability under all conditions. As an aviator, I much prefer to trust my life personally to get into a machine and realise that if a certain something which can perform for him the greater portion by skilled pilots, of controlled manoeuvres which could not be performed by any automatic controls then contemplated. Pégoud repeated his feats soon afterwards at Brooklands. Two months later B. C. Hacks, who earned his living as a display pilot, became the first Englishman to perform aerobatics.

The stage was now set for a series of inherently stable but continuously controllable aeroplane designs which would have no essential need for artificial stabilisation. Such machines would dominate the skies of France later in the war which was to start within a year.

5. LAWRENCE SPERRY

On June 10, 1914, in what would seem, for some time, to be a parting gesture by the “automatists” school, the scene was fit by a veritable super-nova of engineering skill and practical accomplishment. Although the development of aeroplane automatic controls would almost cease for the next few years there occurred an event which would later determine the course of their development for aircraft right up to the present time. On this day Lawrence Sperry demonstrated from the Seine at Bézons the fully automatically stabilised Curtiss flying boat which the Sperrys had been developing for several years[29]. The machine was entered for the aeroplane safety competition (Le Concours de la Sécurité en Aviation) which the Aero Club of France was conducting on behalf of the French War Department. The demonstrations were preceded by elaborate but lucid press releases and were arranged to give the most dramatic impact, which later included taking several judges on flights. The Sperry Gyroscope Co. was awarded the top prize ($80,000 francs; at the time £2000 or $10,000 which covered the $8000 which it had cost the Gyroscope Co. to develop the stabiliser). During the demonstration the judges and spectators were treated to the sight of the aeroplane flying steadily at low level under automatic control, which Lawrence Sperry standing in the cockpit, holding his hands above his head, and his French mechanic, was making from a standing on a wing (Fig. 7). The system used by Sperry could be a very elegant piece of engineering and weighed about 40 lb, less than the simpler Dootre Speed Stabilizer. Like the Dootre device, it was also primarily a mechanical/pneumatic system, and used electricity (ac generator) only to drive the wheels. It had two axes of control, roll and pitch, the attitude sensing in each axis comprising a pair of counter-rotating gyroscopes (with a weight of 2 lb and driven at 12,000 rpm) which coupled mechanically so that precession torques were always in equal opposition. All spin axes were horizontal and each pair of gyro was pendulum suspended in gimbals, the whole being mounted on a single platform. This was the first aircraft gyro stabilised pilot in the form accepted today. Pitch and roll attitude errors operated mechanical roller switches which in turn actuated pneumatic servos to move respectively the elevators and ailerons, the switch operations being cancelled by means of a reliable balance on the central beam. The feedback mechanism used was described by Sperry as an “easing off” device to prevent over-oscillation. There was also a so-called “force-impression” to offset reaction to a false vertical during turns.

A multi-purpose anemometer between the wings measured airspeed which was used to provide a stall protection (a "vel planer" demand for 20° nose down) similar to the French Dootre device, and in addition the airspeed readout was used "to move the fulcrum of the plane’s control levers in such way that the free angles of the ailerons and elevator suited the speed of the aeroplane". This must surely have been the first actual use of parameter gain control, although Maxims had such a provision albeit in his design of 1891. (Elmer Sperry was an avid reader of patent specifications and it is interesting to speculate as to whether he ever studied the Maxim claims).

Other experimenters had proposed the use of signalling gyroscopes before Sperry. By 1911, Dexler in Germany had progressed his earlier design to the stage of using potentialmeter pick-offs on a gyro which could drive electrohydraulic servos, a more sophisticated approach, but to Lawrence Sperry undoubtedly goes the honour of bringing the first system up to a practicable demonstrable standard.

The Sperrys refused to sell their systems to the excited Continentals, despite handsome offers of large orders from Germany in particular. It was in keeping with Elmer Sperry’s principles not to supply his inventions to anyone if he did not consider they had reached an adequate state of development. He had had unfortunate experiences in this respect with his ships stabiliser in Germany, and in the case of the aeroplane stabiliser he was particularly concerned about the unreliability of the pneumatic servos and wanted to replace them with electrical ones.

Certainly the 1914 Sperry aeroplane stabiliser had many problems although it had been under development for several years. A great deal of effort was needed to set it up for each flight, and by today’s standards it was a terribly device that needed constant adjustment. Indeed Sperry had to contend with difficulties similar to those on today’s systems, but without the solutions engineers now have at their disposal. His gyros had a relatively high free drift rate, and therefore had to be made pendulous and hence sensitive to unwanted disturbance. Other problems were friction in gimbal bearings, deadspace and flexibility in the control wires and airframe and because of the unavailability of proportional amplifiers and devices for mixing input signals, his complete system would have been, by modern standards, very difficult to adjust and optimise.
On occasions the high-spirited Lawrence appeared to pay scant heed to the possibility of dangerous malfunctions. Although he had a foot pedal instantly and instant disconnect of his stabiliser in anticipation of such problems he was not always quick enough or even ready to operate it. One report tells of Lawrence making “a long flight sitting on the edge of the boat practically all the time.” Another report describes an occasion when, “bored by office routine, he took one of New York’s glamorous young society matrons flying over Long Island. Lawrence, who never has an opportunity to demonstrate the dramatic uses of technology, activated the stabiliser, . . . but . . . unexpectedly the machine malfunctioned, and the plane plunged into the bay.” Lawrence was once described by a friend as “a real genius, a terribly hard worker, and one who had no leisure.”

Lawrence continued his developments through 1917 when America entered the war, but at this time diverted his efforts to the design of a so-called “serial” torpedo which was intended to perform much the same task as the German VI did in the latter part of the Second World War. The automatic controls required were a logical development of his 1914 stabiliser, involving a change to electrical switches on the gyro to operate the servos and the pilot’s skills were reduced to that of checking after the run that the gyro was working. In order to assist the pilot, the skill required was much diminished in a machine of this kind.

These additions to the basic stabiliser during the First World War, especially the automatic steering, added new dimensions to the role of the automatic pilot. They were not only artificial stabilisers, but became what the wear would today call “automatic pilots”. (They were first called “gyropilots” by Sperry.) Although during that war there was little development of “automatic flight”, Sperry, with his splendid pilotless bomb system, in 1916 Mr. D. T. Glass-Hooper anticipated the current concept of “electrical signalling” by 50 years. The gyro equipment on the bomb would operate the servos and turn indicators on the propeller shaft and “at the exact moment it would operate to dive the plane into its destination.”

The control levers were now not only artificial stabilisers, but became what the world would today call “automatic pilots”. (They were first called “gyropitols” by Sperry.) Although during that war there was little development of “automatic flight”, Sperry, with his splendid pilotless bomb system, in 1916 Mr. D. T. Glass-Hooper anticipated the current concept of “electrical signalling” by 50 years. The gyro equipment on the bomb would operate the servos and turn indicators on the propeller shaft and “at the exact moment it would operate to dive the plane into its destination.”
controls and gain adjustments to assist with the setting up for any particular flight. The reports on flight testing of the device also pass quickly over the problems presented by gusts. George Aveline claimed that the system was superior to the Sperry gyroscopic one, although it was considered by some an unnecessary refinement. It has, however, been shown that the system can be made gyroscopically stable by making suitable adjustments of the gyro's and of the linkages.

The Aveline device, and other contemporary inventions, were important indications of the new upsurge in interest in automatic controls, both for minimizing the fatigue of the pilot and for improving the performance of the aircraft, especially in rough weather conditions. However, many of the developments which arose in the early 1920s were of little use and nothing came into practical use until about 1934, partly as a result of the Sperry 1914–16 systems. Indeed there was never to be a completely new concept to supersede the Sperry, and it was improved and extended to meet changing demands by the aircraft industry and by scientists and engineers to progress the design of the basic elements of automatic control systems.

Remote sensing devices were always of considerable interest to the Sperry company. Wünsch, for example, had worked in Germany, in 1924, to develop a successor to the remote sensing "Selten" system, which had a limited accuracy, and which could provide the ailerons with a speed of 1000 to 5000 to feed robust remote sensing instruments, by means of a control unit which could also be used to derive a speed signal of 1000 to 5000. The control unit could also be used to derive a speed signal of 1000 to 5000. So the Sperry 1914 stabiliser had a retractable radio cable.

In Germany, Sperry had presented both the government and industry with a team of engineers and scientists to progress the design of the basic elements of automatic control systems. Remote sensing devices were always of considerable interest to the Sperry company. Wünsch, for example, had worked in Germany, in 1924, to develop a successor to the remote sensing "Selten" system, which had a limited accuracy, and which could provide the ailerons with a speed of 1000 to 5000. So the Sperry 1914 stabiliser had a retractable radio cable.

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be sufficiently sensitive to control long period instability (e.g. the phugoid) without aggravating an unacceptable degree of the short period aircraft instability. The means of the best optimisation was not really understood at the time.

The performance of the pneumatic servo was limited by the elastic fluid and by stiction in the servo control valve. Under operational conditions, lack of lubrication (the compressed air tended to sweep everything clean), icing, and dirt in the servo valve caused considerable unreliability.

Later these limitations were also found to be severe in the German Askania, where separate gyroscope system series Lz4 to Lz11 which were used in a wide variety of early Dornier and Heinkel aircraft. Askania abandoned pneumatic systems in favour of electro-hydraulic units.

It is worth mentioning that in the early 1930s electric servomotors were not generally considered to be suitable for automatic controls, as the torque/ inertia ratio was too low in any device of reasonable weight and size and degree of control. However, there were some German systems in the 1930s which used Ward-Leonard coupled electrical drives or continuously running motors from which power could be clutched mechanically into the controls as required.

The early 1930s marked the first commercial use of autopilots when Eastern Airlines installed a Sperry A1 in a Condor, one of the last of the commercial aircraft bi-planes. Sperry had their A2 under construction in 1933, this being the main competitor of the Mk 1. The A2 and subsequent A3 had some special features and some significant ergonomic problems (Fig. 13). These were attitude/ control displacement systems of the “pilot-assist” category. The functions of the pilot’s instruments and automatic control were combined, which was fundamentally a good economic approach but meant that the gyro could not be precessed to achieve max in the Mk 1. Combing the instrument and autopilot sensing also removed the ability to cross-check the operation of the two.

The significant design point about the A2 and A3 gyro-pilots however was that they provided in effect a modular selection of sensors and servos which the pilot could employ as he wished.

During the development, the gyro could only be engaged from a trim condition and the data was displayed on an instrument and a servomechanism for any control movement. Although the position and speed of the control was displayed on the pilot’s panel, it was not displayed in the cockpit.

The A2 and A3 therefore achieved a reputation for high reliability because if they didn’t work very well at any time there was a reasonable chance that the fault arose from pilot misjudging, and it was therefore difficult to substantiate a snag in performance.

Engagement of the gyroscope required care and was carried out apprehensively. Slow turns were demanded by the rudder knob and larger turns by operation of the aileron knob. There was no automatic turn compensation in pitch or yaw.

In 1933 the capabilities of autopilots were dramatically shown by two record-breaking long distance flights. Between July 15th and July 22nd, Wiley Post flew solo around the world in his Lockheed Vega, the “Winnie Mae”, in 7 days, 18 hours and 49 minutes. The Vega was equipped with a Sperry A2 gyro-pilot after an impressive demonstration of its performance in July 1932 by a Sperry A2 in a Condor. The total distance flown was 21,000 miles, the first solo flight around the world.

In a similar period, Wiley Bennett, also using an automatic pilot, flew 25,596 miles in roughly the same time.

By the mid-1930s there were many autopilots in general service throughout the world in both civil and military aircraft. Most of them employed the principles described, but the market for high-speed single-axis automatic and single-axis stick-operated control units was limited by the effects of unsteady airflow.

A noteworthy example was the autopilot developed in France by Robert Alkan, on which flight trials were conducted in 1936. It was subsequently put into production and was used on the prototype for the earlier Askania single-axis pneumatic system and that there was some connection between the two designs is possible.

Later versions of the Alkan system could be electronically driven instead of air driven gyro wheels and it was also expanded to give a full three-axis control.

Robert Alkan was a design perfectionist who was responsible for many innovations in the flight controls and navigation field. He was one of the most important inventors in the aviation industry, particularly in the area of automatic flight control systems.

Siemens designated their first course controller design K4 which was specifically designed for use in larger aircraft, especially with the K4 used in the Dornier Do 17 and Heinkel He 111 aircraft. The K4 had a very simple design and was a fly-by-wire system, which made it very similar to modern commercial aircraft flight control systems.

Glasnost was the term used to describe the opening up of the Soviet Union to foreign countries and the West during the late 20th century. During this period, the K5 was used extensively in the Soviet Union and the East German states.

The K5 was a gyrostabilised flight control system that was developed by the German company Blaupunkt and was used in various aircraft, including the Messerschmitt Me 262 fighter.

The K5 system was based on the concept of using gyroscopic sensors to measure the orientation of the aircraft and then using these measurements to control the aircraft's systems, such as the elevator and ailerons.

The K5 system was designed to be highly reliable and had a number of redundancy features, such as multiple gyros and backup systems. These features were necessary to ensure that the system could continue to function even if one of the primary systems failed.

Despite the success of the K5 system, the German aircraft industry was not able to keep up with the technological developments of the United States and other leading countries. As a result, many aircraft designs during the Cold War were based on older technology, such as the K5 system.

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consisting of a pair of hot-wire bolometer elements. A blade carried by the detecting gimbals, cut off one or other of the hot wires from an air jet. The differential change of the bolometer resistances, due to course changes, upset the balance circuit which gave rise to the dc output signal. This was, combined with the fine wire rate gyro potentiometer output to feed the magnetic amplifier, which in turn drove a moving coil galvanometer which actuated the hydraulic piston valve. The bolometer was motor driven from the pilot's controller to provide a turn command capability. The complete system weighed 35–40 lbs.

For the Mk IV a special high accuracy computer had to be designed which incorporated displacement, rate, acceleration and integral terms, some aspect of this design being necessary to compensate for the inexact response of the standard Siemens servo actuators being used in this application for which they were not designed.

9. THE SECOND WORLD WAR

The major British system from the mid 1930s was the RAE Mk IV, developed under the leadership of F. W. Meredith. This autopilot was to become very well known in the Second World War to pilots of Wellingtons, Stirlings, Halifaxes, Sunderlands, Lancasters and others.

The Mk IV was a pneumatic three-axis system, with two twin gimbals, one for rudder and elevator control and the other for aileron control, as in the previous Mk I. The difference was that the new machine was a whole new design, following the current US and German trend, but a direct mechanical feedback link was maintained using Bowden cables.

In principle the system was very little different from the Mk I. Unfortunately it proved impossible during the last war to get the production rate of this system above about 500 per day due to the limit on the availability of precision workers to build gyros and servo-motors. This became one of the major bottlenecks for Bomber Command, especially when the long distance raids into Germany commenced, and the need for an automatic pilot, known affectionately to the aircrew as George, was at its peak.

A great deal of effort was therefore devoted to trying to design a system which was simple to produce but would nevertheless meet the prime requirements of the RAE. Work to this end was put in hand as early as 1934 and the first outcome was the Mk VIIIB. The basic idea was to use a single two gimbals gyro only to give a combined roll/yaw control via ailerons, to leave the rudder free with no automatic control, and to drive the elevator from airspeed and error rate.

A new design system had the requirement for gyroscopes and had two instead of three servomotors. It therefore promised to give a considerable production saving compared with the Mk IV, and was pursued for this reason only. The first trials proved satisfactory, but in time another important lesson in automatic control history was learned. This was that barometric rate information, especially used rate input, was not a good term in gusty conditions. The RAE tried hard to get this system to work, but the control of the elevator from airspeed terms was eventually abandoned. Instead a further output was taken off the inner gimbal of the single roll/yaw gyro, and used for elevator pitch control. This gyro arrangement was also merely an experiment, as it was really satisfactory only in level flight. Turns had to be done either manually, with the autopilot disengaged, or automatically by manipulating the pilot's pitch controller to keep up. Despite this unsatisfactory operating feature, brought about by the economical single gyro concept, the system was accepted by the RAF and was designated the Mk VIII. It subsequently became the basic installation in the later variants of the Lancaster and Lincoln.

The system was also coupled to a magnetic compass to give automatic course keeping, as had been a feature of the German course controllers from the mid 1930s. The Mk VIII, as inferred before, would not perform automatic turning onto a magnetic heading, but could be locked onto any heading achieved manually. The directional monitoring of the gyro by the magnetic remote reading compass was effected by impinging an air jet on the appropriate gimbal to precess the gyro. The whole system was barely stable, and in fact the "jinking" excessive action could be programmed automatically by making the system deliberately unstable, giving a ±15° amplitude roll with a 30 second period. It is said that the RAEE flight test engineers who developed this aspect of the Mk VIII found a use for its host-shaped lid which was not related to keeping dust out of the precise gyro. This automatic jinking system was not used finally in service.

In 1943, production levels of the Mk VIII system increased to 50% above the Mk IV, thus justifying the adoption of a less sophisticated technical solution.

One of the major problems of the Mk IV and the Mk VIII as used in the Second World War was lack of synchronisation of autopilot demands and flying controls prior to engagement. This was most serious in pitch, as the datum position of the control column varied considerably depending upon the aircraft loading. fuel usage, and crew movements. It was necessary to ensure smooth engagement and in order from the cockpit "standby to engage autopilot" was an invitation to tighten straps. Later modifications were included to eliminate this engagement problem by a synchronisation action as was current in the US autopilots. Other minor changes evolved the Mk VIII which was installed after 1946 in the BOAC Lancastrians, Halton, Solent and York aircraft.

During late 1945 a number of accidents to British aircraft were traced to dirt in the drum and swarf in the pneumatic servos. To deal with this the control of manufacturing quality was improved, as was also the on-board filter system. In this case control term matching was again improved, and hosted these were negative feedback levers between the output rams and input valves which incorporated deadspace so that they were normally ineffective. However if a valve at any time stuck in a hardover position it would be freed by the release of the "bonker". From this time increasing attention was paid to the safety problems in the design of high authority servo controls and engage mechanism.

In addition to those already mentioned, a number of American autopilots came into wider use later in the war. These were the mainly C-1, from the Minneapolis-Honeywell Regulator Co., the General Electric Co. (USA) Mk IV and the Sperry A-5. All were fairly advanced designs.

The Minneapolis-Honeywell C-1 was an all-electrical system which served as an all-purpose autopilot and worked also with the Norden Stabilised Bombing Approach Equipment. Its main feature was a "reversion cut-out" and a single knob turn controller. It also had attitude and heading hold modes, and used constant speed motors with electrical clutches as its servo concept. The C-1 was a basic installation in the Flying Fortress (B-17), Liberator (B-24) and Super Fortress (B-32).

The General Electric autopilot was simpler, combining instrument information for pilot and autopilot and used electrohydraulic servos. All of the American systems were basically attitude/displacement autopilots.

The Sperry A-5 was an extremely accurate electrical autopilot using electronically generated first and second derivatives of attitude signals to obtain the very quick response needed when coupled to the Sperry bombight. The servo system was wound using the new concept of force-feedback and had, like the older Askania Lz14 and Lz17 rudder servos, a self-contained electric motor/pump and reservoir. The A-5 system was well ahead of its time in this respect and would now be described as "power-by-air". However, it was still rather complicated. As fitted to the Flying Fortress and Liberator, the maintenance was rather high and it proved to keep the system operational proved to be such a burden that installation of it was avoided whenever possible in favour of the more basic Minneapolis-Honeywell C-1.

A later Sperry system, the A12, was similar to the A-5, but employed electric instead of electro-hydraulic servos. This version of the Liberator and after the war gave excellent service in civil aircraft.

One outstanding automatic flight controls development of note was that made in Germany for fighter aircraft. The Luftwaffe required a simple and lightweight course and control system suitable for fighter aircraft in good and poor visibility and which could be produced in large quantities. One of the major problems was to cut down the high loads sustained in delivering aircraft to the front. Wartime fighter pilots are often bad navigators. There was a desire to minimise or to avoid the use of devices such as free gyro's, with their attendant precision production problems, just as there was in England, when the Mk VIII was evolved from the Mk IV.

Siemens set out to design such a system as early as 1933 and 1934, using a spring, and finally produced a series of controllers of which the most successful was the K3. The key to this design was to engage the rate gyro. The system was simplified so that, in contrast to the previous design, there was no need to use a gyroscope. The rate gyro was used to control the autopilot, and a dc electrical servo controlled by a polar amplifier was used. This allowed a simple, lightweight and cheap system to be produced.
measurement of motor armature voltage and current. The device also included a pendulum feedback: "to offset in cross-coupling. The integration constant" or monitor for the integrating rate gyro was provided by remote reading magnetic compass, and turns could be made up to the range zero torque coil. This was one of the most simple and elegant automatic flight control systems produced up to the end of the Second World War, and in some respects anticipated the "rate-rate" control subsequently widely employed in Smiths in England and Continental Europe.

Another very sophisticated automatic control system referred to previously was the 

"... the solution had to be quite different from customary automatic control, because the latter did not permit the user to continue manual control even if the aircraft was through the primary control (stick, pedal). The problem to be solved was how the human operator and part automatics could live together. Doe's further work on the Hs 129 I solved this problem by letting the automatics apply small corrective moments only to the rudder by means of a small servo tab in superposition to, and practically without interference with the pilot's efforts on the primary control. The latter is of course the key element in the Telematic system for linking to external sources such as radio beacons..."
From the end of the Second World War the general concepts of automatic flight controls throughout the world converged onto a common approach to the problems involved both from an understanding of what was required and also because of the situation of what was achievable from practical technology. The various ideas, inventions and experiences of the past solidified into a universally accepted system.

In an RAE monograph (No. 2.503) published in August 1947, H. H. Hopkins,主任 in the text said, "The classical summary of the aircraft stability and autopilot technology up to that time. The definition of a basic autopilot remains one of the key issues ever to the present day. The way to continue was to change the direct definition, to "define" the autopilot as an "error zero" device, which removes any error from the system. Errors may be defined as the deviation of the control setting from its desired value. Thus, the autopilot is defined as an error zero device, which removes any error from the system.

"Historical development has not followed the above logical sequence: the autopilot problems were treated first, and the error zero concept was applied after four terms..." This last statement by Hopkins and Dunn, correct at the time, was soon to be reversed. It was at this time that civil airlines were contemplating new post-war route structures with higher operating speeds and more moderate bank angles (i.e. not greater than 45°) and smaller angles of climb or dive (say within 5° up and 10° down)...

It is interesting to examine the basic control laws that have been used... the majority of autopilots have applied control in response to angular disturbance in roll (p), pitch (q) and yaw (r): in some cases time derivatives or integrals of these angles are added. The only variations occur in elevator control, which for 2 degrees or less have been used. Thus the basic control laws of all autopilots is given by...

\[ \frac{\text{control}}{\text{desired}} = \frac{\text{error}}{\text{rate}} = \frac{\text{deviation}}{\text{acceleration}} \]

where \( \text{control} \), \( \text{desired} \), \( \text{error} \), \( \text{rate} \), \( \text{deviation} \) and \( \text{acceleration} \) are angular derivatives of the accelerations, elevator and rudder respectively, from equilibrium position, and the system's response is linear.

"It should be noted that a number of autopilots... attempt to establish these equations by producing (say) an error which is proportional to the velocity \( \frac{\text{deviation}}{\text{rate}} \), i.e. \( \text{control} \) instead of \( \frac{\text{error}}{\text{rate}} \). These autopilots are said to use a rate-rate system as opposed to the more conventional position-position system. We don't discriminate between these types since we are concerned with basic control laws: there are of course differences when control engine, etc., are allowed for.

"The addition of angular velocity and acceleration terms on autopilot response is of great importance to the technical control laws. It was found that it is possible to improve the stability of the aircraft because the autopilot is receiving valuable information about the aircraft's motion. Fundamentally, the stability is disturbed by moments, which instantaneously produce angular acceleration, because the angular velocity. In order to restrict angular deviations should logically apply correcting moments as soon as possible. Apparatus appears in other words. We should expect control laws in the form of \( \text{control} = \frac{\text{error}}{\text{rate}} \).

Such an autopilot however would need a steady angular velocity and acceleration to produce a velocity which could be added to the equation to remedy this. It would appear that the further addition of a position term would prevent the autopilot from reacting to a steady angular accelerant. However, it is possible for the equilibrium position of the control surface to change subsequent to the time when the autopilot was first engaged. Thus disturbing moments may be built up due to changes in \( \text{position} \) caused by consumption of petrol, etc. Thus, the rate-rate control system... moments must be balanced by a permanent deviation of the control surface. However, with \( \text{desired} \) as the angle error, which is the time derivative of \( \text{deviation} \).

The trimming term must be of the same variable which is the sum of all the gusts or disturbances which sometimes happens that monitors, essentially to restrict errors of small and low amplitude movements to the surfaces. This was an important factor

in the decision to select this form of control, and was much influenced by the trimming sensitivity of operators and certifying authorities in the late 1940s to the dangers inherent in the use of high authority automatic flight control.

The MK 9/SEP 1 autopilot was a three-axis one using two inductive pick-offs and eight servos of the hysteresis type, which were especially developed for this system. Each axis employed a monitoring device (pandameter in pitch and roll, and compass for yaw) for correcting any error that could happen due to any duty drifts. Turns were demanded by appropriately gyroing the motor platforms with respect to the and the current state of the art was dramatically demonstrated.

The short period of position of the gyro sensor could be distorted by large gusts causing low velocity saturatation, but the hysteresis motor was designed to minimise this effect and the long period position or compass motor was re-established. The amplifiers of the MK 9/SEP 1 were a combination of vacuum tube devices, for handling low signals, and magnetic amplifiers for the servo drives. The vacuum tubes were individually tested and preconditioned before delivery. However, they did not reflect its demands onto the pilot's... system lag.

In a paper to the Royal Aeronautical Society in 1949 F. W. Meredith said: "It is unfortunate that our manufacturers of vacuum tubes (vacuum tubes) cannot see their way to producing special valves for electronic equipment requiring a high degree of reliability. There is a large field in industry for electronic control if the required standard of reliability could be guaranteed, but which are not available because the manufacturers have seen this and are producing special valves for the purpose. Unless something is done about it soon, the job will be done without valves or the art of electronic control will be in danger of becoming an American monopoly." Something was done: a series of "tagged" valves was produced, and many of them were American.

In the United States by 1947 many of the new aircraft on the drawing boards had a greatly expanded speed and altitude range, and exhibited the type of characteristics which Karl Dostich wrestled with towards the end of the World War II. The necessity for "full height" damping had also spread to the larger aircraft, and a considerable amount of work was carried out, notably by the Boeing Airplane Co. to improve the height keeping performance of the XB-47, a four-engine bomber being developed for the US Air Force. They chose the same solutions: a yaw rate gyro pick-up that operators... in the air, and also to improve the "loop" stabilization task (sometimes called "stability augmentation") while maintaining the plane in the environment.
speed and various guidance devices such as radio beam receivers and other sensors deal with the so-called "outer-loop" control requirements, which, for example, include stabilization of the pitch case. Of course the complexity of present day aircraft makes this statement simplistic, however the basic principles remain valid. In block diagram form, a modern automatic flight control system (AFCS) would incorporate "inner loop", "outer loop", logic and pilot's controller aspects (Fig. 18) and would have a large number of potentially interrelated modes of operation.

12. The early 1950s

In Britain the Smiths Mk 9 and SEP 1 transport and bomber aircraft autopilots were followed by the Mk 10. Military systems in the United States also retained a version of the SEP 2, both having radio coupling. These were substantial and highly significant systems and had a considerable impact on British automatic control capabilities. (More than 1000 SEP 2 systems were subsequently produced.)

Both of these systems were in service by the early to mid-1950s. The principles employed were similar to those of their predecessor's, but advantage was taken of advancing technology to substitute magnetic amplifiers for the vacuum tube amplifiers of earlier types. This gave a considerable improvement in reliability. The control modes of the early SEP 9s were attitude stabilization, altitude and airspeed control, glide path, wind and VOR (VHF Omni-Range). It would also turn the aircraft to an alternative heading. The weight was 80 to 110 lb depending on the optional facilities incorporated.

The SEP 2 and its United States contemporary such as the Sperry A12 and the Bendix P100 (which included automatic on the approach) gave to pilots, for the first time, a smooth continuous operating capability which would allow more than 90% of a civil transport to be controlled under automatic control. Indeed, with adequate experience on the transport aircraft of the time, it was possible to have the autopilot engaged down to "break off" heights of only 300 to 200 feet above the airfield, which was not to be improved upon for more than a decade.

Also in the early 1950s, especially in the military field, further significant developments were made affecting automatic control design. First the gyro reference problem was tackled. In the past the gyros associated with the automatic flight controls had suffered from cross-coupling and gimbal locking which restricted the manoeuvres which could be performed under automatic control. For highly maneuverable aircraft it was now decided to produce special gyro platforms to give the aircraft vertical and azimuth references independent of the manoeuvres performed. These references would be available to the autopilot as well as to other systems. In general they took the form of twin gyro assemblies with null sensors and output signals which were sufficiently accurate to ensure that they would be free from gimbal locking errors or toppling dangers.

They would therefore at all times, with fairly high accuracy, give true Euler angle readouts of bank angle, pitch angle and yaw angle. Free-gyro problems were removed from the responsibility of the autopilot designer. A similar design was made with regard to manometric measurements. These were required in the aircraft for a number of purposes apart from their use in the autopilot. The concept of the central data computer was then established. This also took the problems of air data derivation out of the hands of the autopilot designer. These changes really marked the beginning of what is now called "systems integration".

The autopilot designers, relieved of some of their problems, turned their minds to solving others, and to extending the scope of autopilot capability. Automatic radio coupling and automatic landing required a lot of further work and development data and the newly developed hydraulic integrated actuators and power control systems, and advanced stability augmentation systems for high performance jets.

The requirements and the technology available then came together to usher in the present era when whole systems are designed specifically to suit the aircraft in which they are fitted. This was a new approach to the design of automatic flight control systems. The new aircraft were designed for special roles and the automatic controls had to follow suit, or fail.

Indeed from the early 1950s, there ensued such a proliferation of automatic control design, and such a multitude of aircraft types, each with its own special characteristics in relation to automatic flight controls, that it is no longer possible here to cover all of the separate systems individually. For example, if it is appreciated that the Bendix Co. alone, as one of about six major world suppliers, has designed automatic flight control systems for more than 70 aircraft types since the Second World War, the magnitude of the total world activity will be appreciated.

There have however been a number of significant milestones in the development of the technology of automatic flight controls which apply to all of the vast number of separate designs which have come to fruition over the past 20 or so years. Some of these more recent and recent history from a general viewpoint, although in some cases it is still relevant to illustrate the key milestones by mentioning particular designs. Where examples are used these have been chosen from information most readily available, or else from the point of view of the particular advantages or otherwise. Dr. Walter Tye has described this problem rather succinctly "a tree in the heart of a wood must be forgiven if it knows best the trees in its immediate vicinity and if its perspective of the world is consequently limited.

From this point an attempt is made to consolidate both background and frontaul developments so as to get an overall picture of the latest work and the more recent explosion of technology into perspective.

13. ANALOGUE SIMULATION

By the end of the Second World War, as has already been mentioned, the ground-based flight control systems were designed to reduce to the absolute minimum the number of moving parts in the most critical components which were then being demanded. Suitable transistors were not readily available until 1954. The valves (electronic tubes were most unsuitable for use in a short period the magnetic amplifier came again into prominenve. These had been extensively already during the Second World War by the German automatic controls designers, but they did not enjoy anywhere else and most of the autopilots of the immediate post-war period used valves. The magnetic amplifiers of the early 1950s were considerably improved over earlier wartime counterparts because of the development of higher permeability magnets and the availability of the newly developed silicon diodes. They gave a very significant increase in reliability in the "black box" elements of automatic flight control systems, but in the new designs, was restricted to the very few years before the advent of a wide selection of reliable transistors.

It is interesting that a large proportion of the transport and combat aircraft in service in the world today were designed during this brief period and these have automatic stabilizers and autopilots which still employ magnetic amplifiers. In many cases, these were only applied for servo power amplification, as the necessary high power transistors which ultimately replaced them did not become available until much later than the low power ones. However many of the computers designed in the early 1950s also used magnetic amplifiers for basic analogue computation.

The Elliott Mk 13 and subsequent automatic flight control designs were the first to use silicon diodes. Elliott Lightning was a British design which used valves which are representative of such technology. These have magnetic "operational amplifiers" in which the majority of gain adjustments in the computers are effected in the amplifier feedback loops. These also employed the newly available silicon diodes. The Lightning was designed so as to be able to provide a temperature environment similar to that of the German autopilots by the application of the silicon junctions (Fig. 20).

15. HIGH PRESSURE HYDRAULIC SYSTEMS

During the Second World War emphasis was placed on the use of high pressure (3000 psi) electro-hydraulic actuators and power controls, made necessary flight instrument. This requirement was continued to be required to match the existing control demands of high speed jet aircraft. Most automatic actuators were of
limited authority and operated in the conventional way in "series" with the pilot's controls so that continuous demands could be injected into the flying control surfaces without the knowledge of this being conveyed to the pilot through movement of his manual controls.

A different approach was necessary for the "autopilot" or "outer-loop" controls. Before the introduction of the new hydraulic power actuators the main means of coupling autopilot demands to the controls was merely to connect the servomechanism, via a remotely operated clutch, directly to the cables of the corresponding control system in the cockpit. This was called "parallel" coupling as any movement imparted to the control inputs acted on both the flying surfaces and also on the pilot's controls, thus serving the double role of automatic control and monitoring indication. The clutch mechanism essentially incorporated some force limit break-out action for safety if the autopilot suffered a runaway failure, so that by gripping the stick, the pilot could override the system if he so desired.

When hydraulic power controls with relatively low force inputs were introduced (the de Havilland Comet and the Boeing XB-47 were among the first) there was the necessity to give the pilot's controls an artificial feel, and to many pilots it all seemed wasteful if the autopilot actuator should continue to be inserted in the conventional way, requiring a high output capability merely to overcome the "artificial feel".

A proposal was therefore made for autopilot actuators to be integrated into the aircraft's control surfaces. It seems that the main inventions involved simultaneously arose in both England and the USA, and that some one of the inventors stated that a large number of military and commercial aircraft types now use the basic principles involved. These include currently the Buccaneer and VC10 in England, and the McDonnell Douglas Phantom and DC-10 in the USA. The version designed in England by Elliott Brothers (London) Ltd in 1953 (62) was arranged to operate in two modes: 1. Autopilot coupling as any movement provided to substitute an electrical output position feedback for a mechanical one on the main output power surfaces and also on the pilot's controls, thus serving the double role of automatic control and monitoring indication. This was the residue "parallel" and, with many pilots, an un-popular concept.

The Smiths Mk 9 autopilot, with extensive additions, formed the basis of the original BAE experimental systems. Automatic coupling to localiser and glide slope ILS systems was developed for auto-approach alone, comprised the first phase of an automatic landing, and the final approach and landing evolved around the use of a special magnetic leader cable pair, embedded on either side of the runway for accurate azimuth control, and a programmed radio alimeter demand for pitch control. The leader cable system was initially installed for measurement purposes only, and subsequently it was discarded for in-series, as the so-called "pilot-in-the-loop" one.

In October 1958 the BAE announced that they had completed over 2000 fully automatic landings, on several different aircraft, and they released the results of their work to the commercial world.

The BAE was showing that automatic landings could be achieved with high repetitive accuracy, but the failure probability of such a system was too high for civil transport application. There would need to be an alternative safety by allowing the pilot a limited control in the system during a landing. The British view was that the possibility of pilot takeover on instruments could not be eliminated, and in any case the ability of the pilot to perform the "safe" take-over in poor visibility, with the requirement of success, could not be proven by any practical means. It was therefore decided that protection against the effect of failures should be provided by adding further automatic systems, and hence various "failure-survival" or "fail-operational" techniques were investigated.

At the time there were two companies in England which both had orders for new transport aircraft: de Havilland were designing the Trident for BEA, and Vickers Armstrongs the VC10 for BOAC. Both airlines decided to incorporate provision for automatic landing from the inception of design. By this time other blind landing experimental activities were also underway, mainly in the USA and France. By 1958 the Boeing 707, Douglas DC-8 and the Convair 880 jet transports were in service and the main pressures were applied to produce "add-on" blind landing capability to the existing installations. As the single-aisle autopilots in these aircraft could not offer the necessary control and positive operation capability without extensive additions, the main approach became the so-called "pilot-in-the-loop" one. This required continuous pilot involvement in the automatic operation, including the ability to access the autopilot to correct obvious undesirable deviations during the approach and landing on the basis of instrument monitoring. The US National Transportation Safety Board and the operators and the manufacturers all expressed doubts that the British approach to the blind landing problem would find universal acceptance. It was obviously that the risks of robustness envisaged would greatly increase the price of the automatic landing system, in effect a radio, instrument and related ground guidance system aspects.

In the event, many non-redundant system extensions aimed at automatic landing, both by de Havilland and installed in existing US transport jets, but little progress was made by these towards the achievement of blind landings.

One system using only a single landing autopilot with safety not under "blind" conditions was the R. P. Patient management over in an emergency did however come into service. This was developed jointly by Sud Aviation and Lear-Siegler for the Caravelle and ultimately became the first aircraft to perform automatic landings while carrying fare-paying passengers. It is said that the introduction of this great dealt to the easy handling and relatively gentle landing characteristics of the Caravelle.

The pressure for blind landing in Europe in the late 1950s owed much to the frequent occurrence of low visibility, especially in London, and the desire to improve scheduled time-saving determined BEA and BOAC to proceed with the development of automatic landing systems which were provided for in the basic designs of the Trident and VC10.

However the design of these two systems was approached from different viewpoints. BEA required the Trident for short-haul routes in Europe, in order to ensure the regularity of their operations. For BEA therefore, automatic landing was to be a very important requirement. De Havilland and Smiths Bailey, both of them set out to design an automatic system based on a triple failure-survival concept. The Trident was to...
be an aeroplane in which crews would feel sufficiently at home in an automatic environment to allow it to do blind landings when this ultimate development stage was reached. In BOAC the requirements were very different. BOAC is a long-distance airline and the Boeing 707 was required for the "hot and high" routes. BOAC's prime requirement was to control the aircraft safely and without use of any route equipment changes, have a good probability that it would arrive back in London with all systems services still available. The aircraft would have to be equipped with a fair amount of on-board equipment duplication. Hence the concept of a dual autopilot installation in the VC10 was born. However a basic dual installation of this sort would not give the automatic failure survivability required for all-weather landing, but as this was not so vital to the type of operation envisaged by BOAC, it seemed that a time that automatic landing might not finally be pursued on the VC10.

However another factor entered. It was the custom in post-war autopilot design to limit the authority of the systems to safe levels by imposing a maximum fixed torque limit or servo setting normally set to a level which prevented overreaching or over-manoeuvring the aircraft in the most sensitive parts of the flight envelope, while at the same time allowing sufficient authority in the low speed, forward cg condition, especially during approach and landing. The Trident and the VC10, and the US contemporaries for that matter, were intended to operate at relatively high subsonic Mach numbers, and even when the mitigating influence of artificial feel was included it was difficult to achieve a satisfactory single setting for the torque limitation at the autopilot pitch servo coupling point. Hence the systems needed further protection to ensure that excessive automatic demands could not be imposed on the airflow following any autopilot failure. Smiths and De Havilland achieved this on the Trident by virtue of the greatest extent of solid-state philosophy and did not use mechanical torque limiters.

The VC10 retained the torque limiter philosophy based upon the Flexit automatic stabiliser which had the hydraulic principle, but Vickers Armstrongs required this to be supplemented with additional electronic monitoring. This was first attempted with a single extra monitor channel, to serve both of the autopilots. This would have been a single extension of the concept of the Boeing 707. However, the Bendix PB-20D, which was already in service with BOAC, and which was also designed to be indigenous and the basis upon which Elliott would design the VC10 autopilot system. Unfortunately the single monitor concept, although simple at first glance, required two for far too complex to implement in practice. Hence two separate monitors were chosen, this giving rise to the Elliott dual monitor version of the VC10, with both electronic channels maintaining a duplicate set of dual-duel systems later to be used in the transport aircraft produced by a number of manufacturers. The VC10 system then had the basic capability to survive any single failure, as had also been provided by the triple system in the Trident system. Hence it became capable of performing failure-survival automatic landing (Fig. 23).

So much has been written about the details of the design of the VC10 autopilot system, but the systems work well while only relying on the equipment which was specified at the outset in order to cover all eventualities. The VC10 system in particular used most of the existing Bendix PB-20 modules. These were elegant metal cards with "punch through" terminals which allowed a very economic wiring assembly. At this time of largely insurable printed circuit boards was not favoured for automatic pilots, due to the unsuitedly large amount of modification which was demanded in the later stages of flight testing. The PB-20 concept was developed under the leadership of Dr. Norman of the Bendix Eclipse-Pioneer Division at Teterboro, New Jersey.

A major hurdle for the Trident and the VC10 automatic landing systems was certification. These were the first aeroplanes required to rely on some extent upon electronic systems for safety in the critical landing stage of flight. Certification therefore had to be based upon statistical analysis of the redundant equipment installations, as it was impossible to carry out sufficient test flying to prove the levels required in practice. The certification requirements were evolved from around 1960 by the Air Registration Board who laid down that any automatic landing system, in whatever visibility condition it was used, would need to be at least as good as manual landing in good visibility, or preferably an order of magnitude better. The so-called "1 in 100" requirement at the maximum probability of a fatal landing accident under automatic control was thus created and became the criterion for certification.

The automatic landing system concept as generated in England also ensured the associated ground guidance equipment and airport facilities and therefore demanded a total systems approach to safety and regulations. Her Majesty's Government tackled this problem which this was posed with the formation of a special Ministry Directorate of All-weather Operations which was later incorporated into the Civil Aviation Authority.

In the Trident airborne design Smiths employed a triple electric autopilot, using triplex sensors, triplex computing and triplex electrical servos. This matched the airborne concept in which has three engines and three electrical systems.

The VC10 is a four-engined aircraft, with four electrical systems, and elevator and aileron surfaces are in each system powered by four power sources. To match this Elliott used automatic control elements in combinations of two or four. In this early cycle of automatic flight control systems the Smiths' system was the world's first fully triplicated automatic landing system and the VC10 monitored-duplication philosophy spawned the idea for subsequent dual-dual systems and their attendant self-monitored sensor devices. Theremin and Elliott had now available self-monitored radio receivers, self-monitored radio altimeters, self-monitored gyroscopes and so on. Such devices are widely used on the present new generation of civil transport aircraft.

The pitch control (author) facet of the Trident automatic landing system was introduced into service in June 1965. A comprehensive history of the development was presented by R. G. Wilkinson in the Royal Aeronautical Society's Monograph Lecture in 1969 (67). The Trident has to date performed over 20,000 automatic landings in passenger service and is cleared for Cat 3A ( touchdown zone (Runway Visual Range) and down to 12 feet decision height) landings. The VC10 has 3A equipment installation in service since 1968 but is cleared only for Cat 2 automatic landing, having performed consider the power and landing than similar.

17. REDUNDANCY, MICROCOMPUTERS AND DIGITAL COMPUTING

The decade of the 1960s will go down in history as a pro-liferation of primary and associated equipment. Seen have been the adoption of the technology of the space age, particularly that of solid state electronics and the extension of autopilot responsibility to cover automatic landing in very low visibility. The use of redundant equipment for failure survivability also spread from the automatic landing application into other "safe" systems which can extend the operational and performance capability of most types of aircraft. So-called "fly-by-wire" systems are now being designed which will dominantly perform the functions of traditional hydraulic and mechanical systems in an almost entirely digital manner. The "fly-by-wire" is the complete control of the operation from electrical signals derived from the pilot's manual controls and suitable motion sensor feedbacks from rate gyro, accelerometers and such like.

The concept and development of these systems has been spurred on by the drive to automatise the aircraft, and by the potential of such systems for increasing the system of the aircraft. The concept of this has been called "fly-by-wire", though the term is somewhat misleading, as it implies a direct control from the pilot to the aircraft, whereas in reality the control is indirect, via a computer.

The first major step in the development of a fly-by-wire system was the development of a digital computer, which could perform the necessary calculations. This was followed by the development of digital control systems, which could control the aircraft in a much more precise manner. The first of these systems was the Boeing 747, which was fitted with a fly-by-wire system in 1969. Since then, the development of digital control systems has continued, and the technology has improved significantly.

The main advantage of fly-by-wire systems is that they can provide a more precise control of the aircraft, as they can be programmed to perform a wide range of tasks. This has led to improved flight performance, and has also led to a reduction in the workload for the pilots.

The technology has also been used in other applications, such as in the control of missiles and space vehicles. In these applications, the technology has been used to control the trajectory of the vehicle, and to perform a wide range of other tasks.

In conclusion, the development of fly-by-wire technology has been a major advancement in the field of aviation. It has allowed for more precise control of the aircraft, and has led to improved flight performance. The technology has also been used in other applications, and has led to a reduction in the workload for the pilots.
propulsion engine. The automatic system was tripled (i.e., the three lines were designed to be continuously in operation) with fault detection and manual line isolation capability to cope with failures. It was probably the first multiple redundant system, and incorporated one of the first manoeuvre demand systems, the stick movements giving no indication of control surface positions. This type of automatic control was made necessary by the severe handling problems which the design presented, especially laterally. The system used triple hydraulic actuators, relied upon electrical comparison for failure detection, and did not have any mechanical tolerance absorption capability in the actuator itself, which is a feature of most modern counterparts. The SCL was used extensively over a number of years for basic research on control systems, flying qualities handling development work.

Most of the jet lift VTOL designs of the 1950s and 1960s demanded the provision of failure-survival automatic controls as an essential feature of their flight. A notable exception of course is the HSA Harrier, the only design which has come to fruition as an in-service aircraft. The "inherent" versus "artificial" stability arguments which were pursued during the conceptual stages of this aircraft was history repeating itself, when the philosophical dichotomy between the two schools of thought on flight control at the turn of the century is recalled. However, the Harrier does carry an autostabilisers system. This is a simple, single-lane, three-axis system giving short period stability enhancement in the conventional way by using rate gyro feedback. Its special feature is its low weight (only 2 lb per axis including sensors, computing and hydraulic servo power amplifiers). It also has an inbuilt automatic test capability (BITE) to allow first-line testing without the need for ground test equipment (Fig. 24).

An elegant solution to the multiple redundant automatic control problem which occurred during the VTOL NATO competitive period arose from a joint activity between the Italian Fiat Co., Rolls-Royce and Elliott, which resulted in the concept of a VTOL hover rig of the proposed Fiat G95/4 aircraft design. This combined the best concepts of the three companies and computing, and multiple hydraulic actuators.

The rate gyro were self-monitored, and rapid disturbance free changeover to the standby could be effected if a failure occurred in the driving unit. The quadruplex actuator system was hydraulic systems via hydraulic "spring boxes" and hydraulic clutches on a common output shaft and was designed so that the disengagement occurred of any failed section on the basis of majority vote disagreement (Fig. 25).

The system was subjected to 300 hours of tethered flight tests and thoroughly proved both performance and failure survivability of the design.

Unfortunately none of the VTOL aircraft designs using failure-survival automatic controls were put into production, but a great deal of technology in automatic flight controls accrued as a result. For example much of G95/4 system development was continued after the Fiat rig testing and has contributed greatly to the design concept of the automatic flight controls system now chosen for the MRCA, which employs Elliott Fairey quadruplex hydraulic-by-wire actuators (Fig. 26) integrated with the power controls.

The capability for building failure-survival, or fault tolerant systems, has also opened up the possibility on the military side for low level automatic operation in modes such as terrain following. Such a capability was built into the British multi-role strike reconnaissance aircraft, the TSR2 (cancelled following a change in government in 1965, which led an Elliott AFCS of considerable sophistication, using triple and quadruplex flight controls axes to meet a high performance and safety requirement. The system was very advanced, and employed concepts which only now are coming into general use. It was fully transistorised, had a rate gyro and accelerometer actuated stability augmentation system. It received its attitude reference information from an inertial platform and manometric information from a central air data computer. The system had automatic terrain following, the control signals for which came from a forward looking radar. It also had ILS coupling, with automatic throttle control and the normal sophistication of the modern era in using such facilities as fully synchronised operation, automatic trim and integrated coupling to hydraulic controls (Fig. 27).

The very low weight of the Harrier autostabilisers system has been mentioned and this was achieved in the mid 1960s purely because of the new development of the integrated microcircuit. All military and civil systems are now microcircuit design. However its earliest wide scale use in civil aircraft flight control was initiated in 1963 when, rather tentatively, the design of the Concord SST system was built upon microcircuit technology (at that time a bold decision). Without this new electronics capability there is no doubt that the vast technical development which the world has seen over the past 100 years. It comprises six basic subsystems: (a) Auto pilot and Flight Director (b) Three Axis Autostabilisers (c) Autothrottle (d) Electric Pitch Computer (e) Safety Flight Control (f) Integrated Test and Maintenance.

The autopilot is a duplicated-monitoring one which provides automatic control from initial climb, through cruise, to automatic landing. Monitoring techniques ensure "fail-safe" operation in all modes with continuous automatic control and a monitored control channel available during final approach and landing. The system incorporates a landing display giving serviceability information and is designed for the event of an abort, automatic go-around is provided.

A typical autopilot configuration system operates directly into the eural and rudder control surfaces without moving the pilot's controls, and it is arranged that automatic rudder demands are transferred to the servo controls following any engine failure. The three-axis stabilisation system is also self-monitoring, so that there is a great deal of attention has been paid to pilot's control system. The system is designed to be engaged throughout the flight are in a special guarded position located in the roof panel and all mode selection and autopilot manoeuvring controls are on a pilot's control unit in the centre of the flight deck immediately forward of the control columns. In the event of a bank greater than 40°, the autopilot will be engaged and the control surface deflections will be limited. The limit on the control surface deflections will be limited. The normal operating mode is "MAXOP", this single mode controlling the aircraft. Compare this with the 20 operational amplifiers used in the autopilots of the 1940s and 1950s, or the single pneumatic amplifier in one axis of the Askani course control system. The Concord also carries two special-purpose computers used entirely for the purpose of programming the testing of the system and any adjustment failures when they occur in the automatic flight control installation.

18. TODAY: THE SUPersonic AGE

The Concorde automatic flight control system design is representative of the third point in the first 100 years of development and use of automatic flight controls, not only because of its technical detail, but because it arises in an era which is now not only the one of the "project management" team but also an era of international collaboration. Projects of such magnitude are no longer likely to be brought to fruition other than by drawing upon the resources of more than one nation.

The Concorde is a joint effort by Elliott in England, SFENA (Société Française d'Équipements pour le Vols Aériens) in France, and during early development also by the Bendix Corporation in the USA. This system is therefore worthy of some detailed description in order that the reader is left with a final idea of the vast technological development which the world has seen over the past 100 years. It comprises six basic subsystems: (a) Auto pilot and Flight Director (b) Three Axis Autostabilisers (c) Autothrottle (d) Electric Pitch Computer (e) Safety Flight Control (f) Integrated Test and Maintenance.

The electronic implementation is based upon linear computing elements and digital integrators, and associated external components to set gaging transfer functions. The circuits are arranged on stacking modules which mount into the sides of the boxes, which themselves provide physical segregation between "command" and "monitor" computing areas to preclude the possibility of common failures. Solid state logic switching circuits are isolated inside a common central spine. All computers have digital inbuilt test facilities which can be activated by means of a parallel digital data highway from the ITEM computer, the result being displayed on the flight deck. This BITE system has been limited in complexity so as not to increase the weight of the system (any dangerous failure) of the total system by more than 15%.

The complete Concorde electronics is packaged into eight types of computer unit, each being duplicated. These are:

(i) Autopilot & Flight Director Pitch Computer
(ii) Autopilot & Flight Director Azimuth Computer
(iii) Autoabser Controller
(iv) Autohodrol Computer
(v) Electric Pitch Computer
(vi) Warning and Landing Display Computer
(vii) ITEM Computer (Integrated Test and Maintenance)
(viii) ITEM Computer (Integrated Test and Maintenance)

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A great deal of attention has been paid to pilot's control system. The system is designed to be engaged throughout the flight are in a special guarded position located in the roof panel and all mode selection and autopilot manoeuvring controls are on a pilot's control unit in the centre of the flight deck immediately forward of the control columns. In the event of a bank greater than 40°, the autopilot will be engaged and the control surface deflections will be limited. The limit on the control surface deflections will be limited. The normal operating mode is "MAXOP", this single mode controlling the aircraft.

There are no less than 33 modes of operation available for these controllers, and a separate one the system has a Maximum Operating Mode (MAXOP), this single mode controlling the aircraft.

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Figure 26. The Fiat G95-4 quadruplex hover rig system.

Figure 27. The TSR-2 automatic flight control system: 1964.
The system uses a progressive introduction of interlocks. The same weight as a two-axis Aveline stabiliser of the speed or temperature (166 kg) of which 70% is electronic boxes (almost the acceleration from 5000 feet to the supersonic cruise altitude which are uplifted bodily from time to time growth in other fields of engineering technology. The product of the period immediately preceding it, from years from now, the future evolution will show any more by massive mutations.

19. CONCLUSION

It can be seen that over a period of 100 years the design of automatic flight control systems in fixed wing aircraft has escalated in the same manner that has epitomised the growth in other fields of engineering technology. The pattern is irregular and it is doubtful if, one hundred years from now, the future evolution will show any more regularity than it has in the past century. Most of what exists at any time, especially in the field of electronics, is the product of the period immediately preceding it, from only a few years back in general.

The nature of such aircraft, indeed the coming age of such aircraft, so-called Controls Configured Vehicles (CCV) will see the ultimate vindication of the era of Sir Hiram Maxim and those of his contemporaries who pursued "artificial" stability solutions to the problem of mechanical flight.

62. PATRICK, J. E. Improvements in or relating to control systems for aircraft. Patent No 779798.


