Nacelles
ISSN : 2552-6987

11 | 2021
Naissance et affirmation du groupe Airbus (années 1960-années 1980)

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OUTLINE

TEXT

Introduction

1 This article focuses on human-machine interaction in the cockpit of the A320. In the light of current discourses about digitization and automation, aviation technology can be understood as a driver and exemplary testbed for the major societal changes related to these processes. A closer look at the history of flight shows that these changes already started during the Cold War in the realm of military aviation and space flight. In the course of the 1970s and 1980s, analog – and later digital – fly-by-wire systems and computerized cockpits then were transferred to the realm of civil aviation.[1]

2 The history of aviation cannot be told without looking at the process of flying and the role of pilots and their interactions with the airplane. I will therefore tell the Airbus story from the view of the cockpit and ask: How did the introduction of computers in the cockpit change the flying process and pilot-machine interactions? What learning processes and new qualifications were required? Why did the Airbus company decide to change their technology so significantly? One reason is surely the emergence of the required techno-

logy: in the 1970s, it became technically feasible to base future commercial airplanes fully and solely on microprocessors, integrated chip technologies, and fly-by-wire systems. But there were also political as well as economic motivations that justified the risks and efforts required for a major paradigm shift in civil aviation. I will argue that the decision to introduce digital fly-by-wire systems was based on a commercial strategy to strengthen Airbus and with it the international competitiveness of European technology. It was thus also a response to the "défi américain", the fear that Europe was falling behind the United States; by developing the next generation of aircraft, the industry aimed to take a leap into the future and close the supposed technological gap.[2] For the young European company, digitized flight with all its challenges and risks promised an opportunity to take an active role and even a leading position in the industry by defining the parameters of civil aviation for the 1980s and 1990s.[3]

3 In the following, I will provide an introductory historical overview of airplanes as complex technical control systems and discuss the crucial developments of fly-by-wire technology in the 1970s and early 1980s before directing my focus to the A320 and the advantages as well as safety discussions related to computerized flight. This new digital approach to flying can be understood by looking at the changing human-machine relations and their public perception. Airplane accidents in particular reveal how the risks and benefits of computerized flight were negotiated and discussed in the press and media. This paper is just a first step into this crucial field of human-machine interaction. There is much more research needed on human-machine cognition and interactions as well as on "fly-by-wire mode confusion".[4]

1. Airplanes as complex control systems

4 Airplanes are complex, dynamic systems. Multiple forces and factors such as thrust, drag, lift, weight, and wind determine their performance and the pilot's behavior. Yaw movements occur around the perpendicular (yaw) axis and have to be controlled by the rudder in the back of the airplane. The horizontal pitch movement around the lateral (pitch) axis is altered by the elevator on the tailplane, and the roll

movement along the longitudinal (roll) axis is altered by the wing ailerons. In order to control these motions and interferences around the three axes, the pilot's active steering actions, the aerodynamic design and layout of the airplane, and assistive active control devices come into play.

5 Aviation historian Charles Gibbs-Smith identifies two distinct philosophies regarding the control of aircraft.[5] While the early "airman" such as the Wright brothers had to actively control inherently instable airplanes, the "chauffeur" pilot instead passively steers a stable airplane. This stability can be realized "naturally" through the aerodynamic design of the airplane and its control surfaces or "artificially" through mechanisms and devices, such as autopilots, that are placed between pilot and machine to automatically control the direction of the airplane. Any computerized flight control system has to be able to calculate, monitor, and actively correct the moment-to-moment movement around the three axes of flight. Furthermore, many types of data, including weather, pressure and temperature, altitude, speed and acceleration, motor conditions, radio communication and radar, flight path, etc. have to be taken into account and contribute to the complexity of the process of flight. Large airplanes used for long-distance flights require a multi-person crew to perform the many different tasks in the cockpit such as navigation, communication, and control of the airplane's engines. A single pilot alone would not be able to carry out all these manifold control functions. The history of flight shows, that – as in many other branches – processes of automation and digitization replaced human functions and reduced the crew number from five persons – pilot, copilot, navigator, motor engineer, radio communicator – to two in the forward-facing cockpit, or even to only a single pilot plus many computers in military aviation.

6 "Intelligent" technologies that can correct the course and position of ships or airplanes have a long history that goes back to the first half of the twentieth century. Artificial mechanisms to stabilize flight were already devised before the First World War.[6] The tendency to automate flight began early in aviation history, especially in the case of large and heavy airplanes used for long-distance flights. Pilots' workload was to be reduced and the course automatically adhered to by autopilots. The continuous and systematic development of elec-

tronics, gyroscopic instruments, and hydraulic mechanisms paved the way for computerized flight. Gyro-based, electro-hydraulic systems in particular can be seen as direct precursors of computerized analog and later digital flight-control systems.[7] An example of artificially achieved stability in high-speed military aviation is the yaw damper developed for the Me 262 in the year 1944 by Karl Heinrich Doetsch at the German Aviation Research Facility (Deutsche Versuchsanstalt für Luftfahrt, DVL) in Berlin-Adlershof.[8] Another important early example of computer-based flight control is the “Mischgerät” (“mixing device”), an analog computer that combined the input from multiple gyro systems to automatically control the flight path of the ballistic missile V2.[9] This device was developed by the engineer Helmut Hölzer (1912-1996) at Peenemünde in the years 1941 to 1945.[10] After the Second World War, German flight-control technology experts were transferred to France, England, the Soviet Union, and the USA. Karl-Heinrich Doetsch (1910-2003) worked for the control division of the Royal Aircraft Research Establishment at Farnborough and was involved in the development of the electric flight-control system of the Concorde.

2. Why fly-by-wire? A paradigm shift in military and civil aviation

7 What motivated the introduction of fly-by-wire systems to replace mechanical cables and rods, first in military aviation and then in civil aircraft? Use of fly-by-wire systems had already begun to be tested by the late 1950s and 1960s, and test pilots had found them to be reliable and provide superior flight control. Yet because of safety considerations and a certain cultural reluctance to replace cables and rods and even central functions of the pilot with a computer, some time passed before these highly automated systems were implemented on a wide scale and transferred to commercial aviation. For this paradigm shift to take place, it was not only a question of technology, testing, and experience, but also of changing pilots' behavior, as well as the values and images associated with flight in the context of social, economic, and cultural processes.

8 Initially, fly-by-wire systems were especially relevant in the realm of high-speed military aviation.[11] The Cold War created a demand for

supersonic high-performance jets and intercontinental missiles. These required automatic control systems based on processes of miniaturization and microelectronics. Fly-by-wire technology is a consequence of the Cold War period, when the design of combat airplanes reached its structural limits of the technology in use up to that time. By integrating electrical systems that operated together with the pilot, faster and less structurally stable airplanes with a higher degree of maneuverability could be designed.[12] Without these technologically mediated systems, flying these new machines would not have been possible any longer, at least in military aviation where the physics of flight and the complex flight and weapon technologies surpassed the pilot's physical and cognitive limits, especially in single-seater airplanes.[13] Automation changed, redefined, and even replaced many functions and roles of the pilot and the cockpit crew to the extent that today, airplanes can fully fly by themselves and even overrule the pilot's command and main control functions.

9 Important steps towards digital flight were taken by the US in its Apollo Program, which relied on highly sophisticated computers. The lunar landing module and the command capsule were equipped with a digitized control computer for navigational purposes. The astronauts could give their orders by typing words into a keypad.[14] These technologies then were intensively tested and transferred to other areas as part of a NASA research program. After the successful lunar landing, the digital equipment of the Apollo computer was successfully adapted for a conventional airplane cockpit. This is the moment that the digital computer "took flight", as James Tomaykoo has shown in his book on the history of the NASA fly-by-wire research program in the 1970s.[15] One of the main safety challenges for digitized systems was the development of reliable software and designing control functions to have redundancy in case of malfunction.

10 Historically, aerospace industries and microelectronics have been closely linked and even mutually interdependent; this played a decisive role in the development and use of digital computers to design, calculate, simulate, and control the flight of missiles and military airplanes in the Cold War.[16] While initially digital computers were used to calculate flight data and to simulate flights on the ground, miniaturization processes later made it possible to include smaller and less expensive digital computers onboard. At the same time, hard-

ware and software were becoming more and more complex. One key innovation was integrated chip technology, which in the 1970s was ripe for commercial applications. The rapid rate of development of this technology was recognized by industry experts such as Gordon Moore, who predicted a significant cost reduction and power increase over the coming decade; his observation has come to be known as Moore's law.[17] For aircraft, it meant that sophisticated control instruments could be built that could calculate and store more and more data and programs while taking up only a small amount of space. Integrated chip technologies and microprocessors were used and further developed by the aerospace industry, especially in Silicon Valley with its high density of both aviation and electronics companies.

11 Institutionally, the preconditions for a transfer of this technology from military to civil aviation were favorable. Often the same enterprises that specialized in electronic instruments and equipment for military airplanes also had the expertise to develop and produce the necessary digitized equipment for commercial airplanes as well. European companies such as Thomson and Aérospatiale had acquired the necessary technological know-how through their production and development of military airplanes and cooperation within other NATO states, especially the UK, and the US, as well as German companies such as VDO (Vereinigte DEUTA-OTA) that produced tachometers and the Bodensee-Gerätewerke, which specialized in flight instruments.

3. The analog fly-by wire system of the Concorde

Fig. 1. A view into the cockpit of the Air France Concorde F-BVFB at the museum at Sinsheim / Germany

(Christian Kath, May 2006, https://de.wikipedia.org/wiki/Concorde#/media/Datei:ConcordeCockpitSinsheim.jpg, last accessed 29 November 2021)

12 Several factors favored the transfer of fly-by-wire technologies from the military and the space race to the realm of commercial aviation in the transitional era of the 1970s[18] – a period marked by a radically changing world economy, growing environmental concerns, and the rising demands of Western consumer societies. All of this had an impact on the design of the next generation of airplanes. The French-British Concorde was the first commercial airplane to rely on analog computers and fly-by-wire control. This "superbird" embodied the high-tech orientation and optimism of the 1960s jet age.[19] However, the time was not yet ripe for such a technologically sophisticated supersonic jet; marketed mainly to the international jet set and business elite, it turned out to be a commercial failure that did not fit into the context of the 1970s, when fuel and cost-saving commercial airplanes

with silent engines were favored to meet the needs of growing mass tourism.[20]

13 Nevertheless, the cost-intensive development and production of the Concorde by the European aviation industry laid important groundwork in the realm of advanced flight technologies and avionics. The control system was developed by the French company Aérospatiale and the British Dowty Boulton Paul, which had already worked on control systems using electronic signals for the Tay Viscount aircraft; released in 1957, the Tay Viscount was "possibly the first aircraft to be controlled by a fly-by-wire system".[21] The Concorde had a redundant analog-computer-based fly-by-wire system along with a conventional steering system with mechanical rods as an emergency backup. Fly-by-wire was chosen because the supersonic aircraft was subject to the extremely high flight forces, so that fast and precise control commands were required. Developing the Concorde had shown that the fly-by-wire technology could solve many reliability problems associated with the systems then in use; it thus provided a motivation for replacing mechanical systems with fly-by-wire technology as the main control mode of a future "Super Concorde":

> It would be attractive technically to see this form of control on the "Super Concorde" or some aircraft of the 1980 era and studies at present in hand may well show that weight could be saved by taking this next step. Suitably engineered, overall system simplification should be obtained. With such a system the pilots' signals would be added to those coming from the automatic pilot and the autostabiliser, the summed signals would be processed as necessary to give the required flight response and the control surfaces would then be commanded accordingly.[22]

14 In the case of analog computers, the programs were "hammered" directly into the hardware and thus adapted for one specific purpose and airplane. They were less flexible than programmable digital systems, but fulfilled similar functions as the later digital systems with a high degree of reliability. Yet analog systems had the problem that their signals tended to become corrupted through external impacts and over longer distances. Therefore, digital computers promised to have several advantages over analog ones: They were more precise, faster, and above all, more flexible. On the other hand, analog com-

puters seemed safer and more suitable for carrying out single specific functions. Thus, in the course of the 1970s, the development of digital flight management systems focused on ensuring a high degree of reliability and redundancy, especially in the software realm.

4. Airbus introduction of fly-by-wire technology

15 State-sponsored high-tech endeavors evoke far-reaching and often overrated expectations of technological progress and basic innovation. The introduction of fly-by-wire technology went hand in hand with promises to increase safety, to improve flight conditions, and to contribute to making flight in generally cheaper, better, and possibly even faster in the future. In the context of European high-tech politics, Airbus was competing in a market that was extremely difficult and risky and required financial and technological resources that went beyond the capacities of individual companies.[23] Airbus's introduction of computers to its commercial airplanes was part of a commercial strategy in which the computer promised to offer tremendous organizational and cost-saving benefits. Computers were crucial for Airbus not only in the realm of the cockpit but also in the overall organization of production. A new modular family system made it possible to integrate complex design and production processes.

> In 1984, the introduction on the A320 of fly-by-wire control as well as a new cockpit design generated an authentic revolution in that area. Electrical control and auto flight unveiled the era of the mass arrival of electronics and embedded systems. In this case as well, this had an effect on Airbus's industrial organization. The whole architecture of the airplane was partially revisited. The mastery of electrical systems became a fundamental specific asset.[24]

16 The paradigm shift towards digitized flight as it was strategically and systematically pursued by Airbus was not a sudden, revolutionary change but a step-by-step development that can already be seen in the cockpits of the A320's predecessors. Important elements of the fly-by-wire system were developed and tested by Aérospatiale in the 1970s and early 1980s and implemented in the A300 and later the A310, a shorter offspring of the A300. The flight control system of the

A300 was already a complex automated system. It was able to control all three axes, had an autopilot, pitch trim, autothrottle and yaw damper. Its inertial navigation system from Litton included a digital subsystem to calculate navigational data. The smaller A310, introduced in 1983, added significant innovations in the way it was designed, tested and produced, as well as the materials used and its cockpit design. Airbus's decision to build the A310 and systematically expand its products into a strategically motivated Airbus family opened a fierce competition in the realm of short and middle-range flights, where Boeing had heretofore dominated the market with its B737 and the B757.

17 The French company Aérospatiale was responsible for prestigious developments in the cockpit design: "Previous experience accumulated by Aérospatiale in electrical flight control systems and the use of simulation, both ground-based and in flight, has largely contributed to the success of the development process."[25] Aérospatiale had already introduced an analog fly-by-wire control system in the Concorde.[26] In 1978 it tested a Concorde with a side stick for the left hand. In 1981 a forward-facing cockpit was tested in the A300B4 program. Avionics and flight-control experts gathered further practical experience with digital computers in the A310 and test flights with a modified A300B, using this to improve flight control algorithms and the quality of flight for future airplanes. These tests took place in the French Centre d'Essais at Toulouse with an A300 test plane and simulators on the ground. According to Christian Favre, chief engineer at Airbus: "These tests showed encouraging results leading to the selection of an architecture including mechanical back-up for rudder and horizontal tail plane controls."[27]

18 Many elements characteristic of the A320 had been implemented in previous airplanes, such as small color-displays in the electronic flight instrument system that indicate flight data and navigational information. The monitors were coupled with a new digital computer of the automatic flight system (AFD) that controls the movement around three axes. The flight augmentation computer (FAC) reduced yaw movements, trimmed the pitch, and ensured that the limits of the flight envelope were not exceeded. The flight control computer calculated air data for the autopilot and the monitors that replaced many traditional instruments. The primary air data were provided by

a digital air-data computer that transformed primary information about temperature and pressure into digital signals and data. The inertial reference system gave digital information about the movement of the airplane. A flight management computer provided navigational information about the flight path and cartographic material for the pilot that was indicated on a flight-path panel. Thus, the A310 was already a highly automated and digitized airplane that paved the way for the A320.

5. Flying the A320

Fig. 2. Modern Cockpit of an Airbus A320 (https://de.wikipedia.org/wiki/Airbus_A320) for two pilots

(Curimedia, Airbus A320-214 Vueling EC-HHA cockpit, 8 March 2011, https://fr.wikipedia.org/wiki/Airbus_A320#/media/Fichier:Airbus_A320-214_Vueling_EC-HHA_cockpit_(5508849819).jpg, last accessed 29 November 2021)

19 There were many innovations involved in the design and production of this new generation of civil airplane. But it was especially the high-tech environment of the digitized cockpit of the A320 that symbolized its aspirations for the future. The forward-facing cockpit, designed by the German sports car company Porsche, offered more

space and a better arrangement of information for the pilots. The most important change in the A320 was the replacement of the central steering wheels with a new sidestick and the use of an electronic system without a full mechanical backup. Its competitor Boeing kept the two coupled yokes and pursued a more traditional pilot-oriented flight philosophy.[28] The digital computer promised to increase safety and efficiency. These flight instruments were intended not only to define the possibilities and limitations of flight, but also to make the pilot's job easier and more comfortable.

20 With the help of fly-by-wire the pilot is able to steer heavy and extremely fast airplanes essentially with his little finger, or even to remove his hands from the steering wheel or control stick altogether. Electric wires and signals have replaced direct mechanical links, such as cables and rods that run from the pilot's control stick or wheel to the aerodynamic control surfaces such as the rudder and elevator.[29] Literally, fly-by-wire means flying with the help of electric wires that transmit the pilot's command signals via the flight control computer (FCC) to the control wings and flaps of the airplane. In this sense, fly-by-wire is directly determined by the steering movements of the pilot and his actions to keep the airplane in its position and flight path. In a broader sense, fly-by-wire systems integrate multiple control functions of the airplane as a complex technical system, with sensors, diverse computers, actuators, control panels and monitors, including many subsystems, computers, and instruments for different purposes.

21 The flight control computer is the central control unit that integrates flight data, flight laws, and the commands of the pilot.[30] It uses digital general-purpose computers consisting of hardware and software components that allow flexible configurations for different flight conditions. The limits of flight are defined by flight rules and the so-called flight envelope that determines the airplane's maneuvers in relation to height, altitude, change of speed, and angle of attack. To ensure a higher degree of safety, the computer is able to control and even override the pilot's commands and thus prevent the plane from exceeding certain dangerous limits and reduce the risk of stalling (flight envelope protection). As Steve Last writes regarding the implications of this system for the pilot:

> (t)he greatest benefits to the line pilot appear to be, as predicted, and initial reservations about maneuver limitation in extreme situations seem on balance to be more than countered by the freedom to apply maximum input without concern. Similarly the asymmetric handling is excellent. [31]

22 At the same time the computer enables the pilot to more actively tap into all the possibilities of flight without being afraid of encountering dangerous limits. In order to fulfil this complex and active control function, the computer has to compare the pilot's commands with the situation of the airplane, calculated on the basis of current flight data that are transmitted by sensors to the central command unit. Here the programmed flight envelope of the airplane is stored along with the corresponding flight control laws – that is, the algorithms that translate pilot commands into adjustments of the plane. The corrected commands are calculated and transmitted to the actuators that change the elevators and flaps of the airplane and thus the airplane's movement around the three axes of flight.

23 The decoupling of the pilot's actions from the plane's response implies an alteration of the flying experience and a loss of "flight feeling". There is no physical feedback from the aerodynamic control surfaces back to the pilot. The detachment of the pilot from the direct physical forces of the airplane reduces the pilot's physical workload and shifts his awareness to the monitoring of the flight data and panels – a function that in former times was conducted by the flight engineer. The sidestick does not have to be activated throughout an entire flight maneuver; rather, it initiates the maneuver and then lets the machine do the flight. Test pilots with their affinity for new technology particularly liked this new approach. For commercial airline pilots, however, highly computer-mediated aircraft meant having to adapt and learn to fly a new way. Indeed, highly automated computerized flight also has certain disadvantages – for example, when responding to sudden extreme weather events. A pilot experienced in the physical process of flight might react more quickly and maintain a greater situational awareness. There is a certain risk that "paper and pencil pilots" may lose their flight feeling and experience and depend solely on the computer. In a highly automated cockpit, the pilot had to learn not the overuse the control mechanisms and, in a sense, let

the computer do the rest after giving the command via a short pulse-type movement on the stick: from a line pilot's perspective "(A)s far as handling qualities are concerned, it is very easy to overcontrol the aeroplane in the early stages, and learning not to 'fly the aircraft' all the time is a definite process".[32]

24 A related problem of computerized flight was pilot-induced oscillations (PIO). This well-known basic phenomenon occurs when the pilot engages in a series of contradictory corrections in an attempt to control a plane that is not responding as expected. Instead of controlling the airplane the pilot contributes to an ever-increasing and extremely dangerous oscillation and destabilization of the airplane.

> Because the pilot's actions depend in part on the motions of the airplane in response to pilot commands, the aircraft and pilot dynamics form a closed-loop feedback control system. The pilot is said to be "operating closed-loop" or to be "in the loop". The oscillations can therefore be identified as closed-loop instabilities of a feedback control system.[33]

25 This is extremely dangerous during landing. Pilot-induced oscillations can have many causes, and despite the name "pilot-induced", it is not always the pilot and his or her overreactions that is responsible for the destabilization of the flight situation. Thus, a highly automated flight system can contribute to a loss of control and create problems resulting from difficulties in human-machine relations.[34] In April 1995, for example there was an incident during an attempted landing at Washington National Airport with an Airbus A320.

> Airbus reported, "However, some airline pilots are more prone to overreacting than others, especially in turbulent conditions close to the ground. And in that case, the quicker aircraft response together with the pilot's overreaction can lead to PIO [pilot induced oscillations]." Aerodynamics for Naval Aviators states that: "The pilot-induced oscillation is most likely under certain circumstances. Most obvious is the case of the pilot unfamiliar with the 'feel' of the airplane and likely to overcontrol or have excessive response lag."[35]

26 The report to US National Transport Safety Board revealed the need for a programmed configuration for adverse atmospheric conditions

to allow a more "crisp" response of the airplane during bad weather conditions. As a consequence of this incident, Airbus had to develop a software modification of its ELAC Elevator Aileron Computer so that the response is less sensitive.

6. Public risk and safety discussions

27 Without the computer, fly-by wire airplanes cannot be controlled any longer. This calls into question the dominant and decisive role of humans in the cockpit and redefines the role of the pilot. From an anthropological perspective, it means redefining and renegotiating human-machine relations. While it is technologically possible to fully automate complex technological systems, it is an open question whether societies want and support such systems and the new risks and required new skills and competencies that they entail.

28 Reservations about highly automated "computer cockpits" tended to acquire new force following major flight accidents that challenged the high expectations placed on this new generation of digitized airplanes. Safety and reliability issues are central, especially for commercial airplanes that rely on the trust of a broad and varied consumer base. A major international discussion emerged after an accident at Mulhouse-Habsheim Airport during a flight show in June 1988, just a couple of months after the A320 was officially introduced.[36] Thousands of visitors on the ground and later millions on TV watched as the airplane flew at low altitude and crashed into the woods close to the airfield. Several people died. This was a disaster for Airbus:

> Résumé de l'accident : Dans le cadre d'une manifestation aérienne, l'avion effectue un passage au-dessus de la piste 34 R, une hauteur voisine de 30 pieds, moteurs réduits, avec une incidence croissante jusqu'au maximum possible compte tenu du taux de décélération de l'avion. Pendant la remise de gaz, il touche les arbres peu après l'extrémité de piste, s'enfonce dans la forêt, s'immobilise et prend feu. L'évacuation est déclenchée rapidement mais trois passagers périssent carbonisés.[37]

29 In the following, I will not reassess the real causes of the accident, but rather focus on the public debates and perception of this new airplane. In both technical and cultural sense safety issues are at center stage, because they determine the public acceptance of this new technology. In the aftermath of the accident, a public debate about human-machine relations and causes of accidents were discussed in court, press articles, the scientific community, media broadcasts, and interviews and books by the actors involved in this fatal crash.[38] In this sense aviation is an inherently public technology, as Helmuth Trischler and Robert Budd have shown recently with reference to nuclear technology.[39] In the media and press the complex human-machine interactions were reduced to the question "human or machine?" Did the computerization and automation of flight, as some observers argued, create new kinds of risks by augmenting insecurity in complex situations? Or, on the contrary, did automation contribute to a much safer and comfortable flight, as Airbus and pilots argued in defense of the new digital control systems? Journalists and representatives of pilots' associations as well as Michel Asseline, the pilot who had been flying the aircraft, blamed the computer in the cockpit and accused the official commission as well as Airbus of "whitewashing" the machine: "Le blanchissement de l'avion nécessitait le noircissement du pilote. Mais le pilote était-il tout noir? L'avion était-il tout blanc?"[40]

Fig. 3. The question "human or machine?" is central to the public safety debate

(Cover M. Asseline, *Le pilote est-il coupable?* Paris, 1992)

30 Shortly after the accident, an article entitled "Flying the Electric Skies" appeared in the renowned journal *Science* that suggested that the fatal crash into the woods at Mulhouse might have been caused by a failure of the computer system.[41] Michel Asseline likewise criticized the fact that the pilot's control function could be overruled by the computer and he claimed that Airbus was trying to hide this systematic problem with its digitized flight philosophy: "Il fallait à tout prix masquer le fait que les ordinateurs avaient limité mes ordres et avaient empêché l'avion de remonter."[42] As the data from the flight protocol indicate, the incident involving the Air France Airbus A320 near Mulhouse/Alsace was not the result of a failure of the technology.[43] The official final accident report concluded that the accident had been caused by an irresponsible decision of the experienced chief pilot to fly at low speed at a very low altitude.[44] The airplane

according to the investigating commission, had been in a safe state and functioning the entire time. Thus, the causes were not directly related to the functioning of the machine. The decisive fact that the engines had not reacted instantaneously, but required a certain acceleration time, was declared to be normal.[45] Thus, according to the official commission that investigated the accident, it was caused by a combination of factors – low altitude, low speed. The report also criticized that the chief pilot had been overconfident and had not sufficiently taken into account the specific challenges of the situation he was in. The report concludes that the special occasion of the air show may have contributed to this fatal flight at extremely low altitude. In this prominent case, the safety debate that questioned the role of the computer was not supported by solid facts. Yet to generally conclude that the pilot is the decisive factor would be to ignore the complex and intricate human-machine interaction in such highly complex automated systems and the new skills, competencies and learning processes required of the pilots, especially in dangerous situations.

31 After the Habsheim accident, which occurred at a critical point early in the use of the A320, representatives of Airbus and leading pilots tried to restore trust in the computerized cockpit. In an interview, a German chief pilot from Lufthansa argued that digital control systems contributed to greater safety.[46] The fear that humans will no longer be able to make decisions during flight or that pilots will be replaced by machines would not become a reality, he said. On the contrary, he suggested, the human will be the most "flexible" and "creative" decision-maker in the cockpit.

32 This widely discussed crash near Habsheim was only one of a number of serious of accidents involving this new generation of A320 Airplanes. In February 1990, two pilots crashed their airplane just before the landing strip at Bangalore Airport India, because they were flying in too low and too slowly – 92 people died. In 1992, an A320 crashed into a mountain near Strasbourg at night under bad weather conditions, presumably as a result of the pilots mistaking which autopilot mode was in operation ("mode confusion") – 87 people died. In 1993, a landing at Warsaw Airport failed. There was a problem with an electronic contact of the brakes – two people died. With every accident involving this new generation of airplane, the public debate about human and machine was reopened and the question about the safety

of computerized flight reopened. In 1994, the German news magazine *Der Spiegel* published the headline:

> Series of black incidents in the sky. Airbus under pressure. Twelve wrecks since 1987 with a total of 815 casualties raise doubt about electronically equipped airplanes. Are technical failures partially responsible for this series of accidents? Or are pilots overburdened by the "flying computers"?[47]

33 Senior spokespeople for Airbus tried to counteract the public allegations and mistrust in the cockpit computer.[48] In 1991 Airbus issued an official statement as a response to the continued criticisms in the mass media as well as in response to the pilots' association, which had taken positions against Airbus.

> Parts of the media, on preparing their commentaries, seem to have drawn their conclusions from unsubstantiated opinions before hearing all the facts… and some cases even when in possession of the facts they have chosen to disregard them.[49]

34 Airbus's head of technical development, Bernard Ziegler, stated in an interview that flying is something artificial that would not function without computers.[50] In 1993 two engineers from Aérospatiale published a paper in the journal of the international association for electrical engineering (IEEE). They emphasized the high reliability and safety of the computer systems by pointing at the more than 1,5 million safe flight hours that had been conducted by more than 360 airplanes:

> To conclude, it is worth noting that the A320 flight controls system has "gained good acceptance from airlines and pilots, and that procedures for reporting and analyzing significant problem detected in airline operations are still active".[51]

35 A systematic analysis of flight accidents of the A320 confirms the position that this airplane is one of the "most safest in the world".[52] Yet the arguments and social reservations about a highly computerized cockpit remained and frequently reappeared in the aftermath of flight accidents. For example, in 1997 German sociologist Johannes Weyer criticized the high degree of automation in the A320 and ar-

gued for a more human and pilot-centered control philosophy with higher degrees of active control for the pilot.[53] The argument is that automated systems create new risks.[54] They do not simply reduced the work required during flight, but also introduce an increasing complexity at a new level.[55]

Conclusion

36 The introduction of fly-by-wire systems was motivated by a variety of considerations.[56] Computers – first in analog form and later digital – made it possible to artificially create stable flight conditions with inherently instable airplanes, to reduce the pilot's workload, and to more quickly and precisely correct deviations in the aircraft's attitude and path before the pilot even registers these inadequacies. Instead of being occupied entirely with the mechanical process of flying, with fly-by-wire systems pilots' attention shifts to monitoring the flight and its many subsystems, data, and computers. The computer can perform many tasks of both the pilot and the former flight engineer and thus enables a certain reduction of the amount of work in an ever-more-complex process of flying heavy and ultra-fast airplanes. When the structural limits in the design of military airplanes were reached, electronics systems made it possible to design faster and more instable airplanes with a higher degree of maneuverability.

37 The introduction of fly-by-wire technology in civil aviation in the course of the 1970s and 1980s was motivated by safety issues as well as commercial considerations. Automation promised to reduce costs because computers could do the work of additional crew members – a point criticized by pilots' associations – and also keep the airplane on the most efficient course and thus save expensive fuel. In the case of Airbus as a joint European effort, technopolitics have to be considered a *leitmotiv*. Airbus adopted fly-by-wire systems as a strategy to define the future of aviation and also get ahead in its fierce competition with Boeing. Initially Airbus had to overcome extremely difficult economic prospects and find a niche in an already highly competitive marked dominated by American companies. The development of a whole family of future airplanes based on technological innovations promised a chance for Airbus to prevail over the challenges and risks of a highly competitive market.[57]

38 From Airbus's perspective, the computer contributed to a smoother flight experience, better flight quality, and above all greater safety through the integration of flight control laws that prevent the plane from exceeding dangerous limits. Automation was meant to reduce the pilot's workload and increase the cost effectiveness of flight.[58] However, human-machine interactions in the cockpit have to take into account the habits and constraints of human behavior, including ergonomic and physiological as well as psychological and cognitive dimensions. From the view of the cockpit, digital technology changed the role of the pilot. This role shifted from active steering to a more passive monitoring of the flight data and subsystems. The pilot became an integral part of a complex technological system, not its master, as the classical male pilot image and habitus suggests.[59] Automated cockpits required new skill and training. The crucial question is thus how societies perceived the changing role of pilots and computers and negotiated these new technological risks. Civil aviation is not solely defined by technical experts, but relies on the trust of the millions of people who use these systems daily. Therefore, international public safety debates such as those that occur after major flight accidents could not be ignored by Airbus or reduced to a pure technical issue or a legal matter.

39 Are there lessons that can be learned from this paradigmatic historical example of computerized flight for other realms of automation such as self-steering cars? Both flight and car traffic situations entail a high degree of complexity that has to be controlled by automated systems. Safety issues were at the center of debates and went hand in hand with changing pilots' behavior and skills. After twenty years of development, investments, and technical as well as organizational and behavioral changes, this process has ultimately been successful in the realm of commercial aviation. Yet the risks of automation in civil aviation cannot be fully compared to the even higher risks related to self-driving cars, since here ordinary users are behind the wheel navigating complex daily traffic situations, in contrast to the highly trained and skilled pilot experts who pilot aircraft. Therefore, the question of whether self-steering cars will be introduced on a large scale within the next twenty years will depend on both cost and safety considerations. In addition, the cultural persistence of the

image of the adventurous male driver may hinder the acceptance of self-steering cars.

NOTES

1 I thank Peter Hamel for his helpful comments and expertise.

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3 This article is based on published sources, aviation industry journals like *Interavia* or *Flugrevue*, research reports, and background interviews with scientists from the Technical University Braunschweig as well as with researchers from the German Aerospace Center in Braunschweig who worked with fly-by-wire technology in the research airplane ATTAS (Advanced Technologies Testing Aircraft System). This only represents the initial research phase; a deeper understanding of changing human-machine interaction in the A320 will require further research on test flights, French archival material, and interviews with aviation industry actors from that period, especially test pilots and engineers. Of particular interest is the teaching and training of airline pilots for the A320 at Toulouse and the introduction of flight simulators for airlines as well as design changes after major flight accidents.

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11 The first fully operational digital fly-by-wire military jet fighter was the F-16, introduced in 1972.

12 Electrical wires also were less vulnerable to ground shooting, for example during the Vietnam War. See V. R. Schmitt *et. al.*, *Fly-by-Wire: A Historical and Design Perspective* (Warrendale P. A.: Society of Automotive Engineers, 1998), 82.

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57 The statistics support a success story in the case of the A320, which has sold more than sixteen thousand planes since its introduction. The overall orders logged by Airbus since its creation totalled 20,501 commercial aircraft. See https://www.airbus.com/en/products-services/commercial-aircraft/market/orders-and-deliveries, last accessed 26 November 2021.

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ABSTRACTS

English

This article focuses on human-machine interaction in the cockpit of the A320. In the light of current discourses about societal changes related to digitization and automation, aviation technology can be understood as a driver and exemplary testbed for major societal changes. Since the history of aviation cannot be told without looking at the process of flying, I will tell the Airbus story from the view of the cockpit and ask: How did computers in the cockpit change process of flying? What learning processes and new qualifications did pilots have to undergo to fly and control highly automated and computerized airplanes? What motivated Airbus to decide to so radically change human-machine interactions in the cockpit? Processes of automation changed, redefined, and even replaced many functions and roles of the pilot and the cockpit crew to the extent that airplanes can fully fly by themselves and even override the pilot's command and main control functions. I will argue that for the young European company, digitized cockpits promised an opportunity to take a leading role in the industry and define the parameters of civil aviation for the 1980s and 1990s.

Français

Cet article se concentre sur les interactions homme-machine dans le cockpit de l'A320. La technologie de l'aviation peut être comprise comme un moteur et un banc d'essai exemplaires pour les changements sociétaux majeurs liés aux processus de numérisation et d'automatisation qui sont actuellement largement discutés. Comme l'histoire de l'aviation ne peut être dissociée de celle des processus du vol, l'article traite de l'histoire d'Airbus du point de vue du cockpit et pose la question suivante : comment le vol change-t-il avec l'introduction d'ordinateurs dans le cockpit ? Quels types de processus d'apprentissage et de nouvelles qualifications étaient nécessaires pour piloter et contrôler des avions hautement automatisés et informatisés ? Quelles ont été les raisons qui ont poussées la société Airbus à modifier considérablement les interactions homme-machine dans le cockpit ? Les processus d'automatisation ont modifié, redéfini et même remplacé de nombreuses fonctions et de nombreux rôles du pilote et de l'équipage du cockpit, au point que l'avion peut se piloter entièrement seul et même ignorer et priver le pilote de ses fonctions de commande et de contrôle principal. L'article soutient que pour la jeune entreprise européenne, les cockpits numérisés promettaient une position de leader en prenant de l'avance et en déterminant les paramètres de l'aviation civile pour les années 1980 et 1990.

INDEX

Mots-clés

fly-by-wire, automatisaton, cockpit, ordinateur, pilote, Airbus, humain-machine

Keywords

fly-by-wire, automation, cockpit, computer, pilot, Airbus, human-machine

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