LES DOSSIERS

MORE AUTOMATED, CONNECTED AVIATION by 2050

AAE Dossier #42

2018

AAE

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FOREWORD

Pursuing its reflections into the future of air transport within a 2050 timeline, the Air and Space Academy (AAE) commissioned a study into the progress of automation in this sector. On the basis of work begun in 2013, this dossier includes the findings of a conference organised on the subject in Toulouse in June 2016 and also issues recommendations for the attention of developers, operators and certifying authorities.

More specifically, it endeavours to answer two questions facing manufacturers and operators: How to pursue the harmonious development of automation within a 2050 timeline, whilst respecting the twin goals of safety and economy? What conditions must be met in the long term for a modification in crew composition whilst maintaining the safety level?

On the first point, it is taken for granted that automation will continue to advance, thanks to technical breakthroughs and also due to operators' demands. However, some precautions must be taken to enhance the interface with the crew, given our knowledge of the functioning of the human brain.

The second point is in response to recurrent mention of the possibility of reducing the number of pilots on board, or even of doing away with them entirely. Indeed in America, experiments have been carried out for some years with medium-size aircraft, in real conditions. In order to develop a rational approach to this topic, our study looked specifically into the possibilities, and their limits, in the field of flight safety. The technical solutions examined are judged to be certifiable, but their cost-effectiveness can be assessed only by industry and operators.

Although this dossier is the result of collective reflection, the reader will note that the work comprises chapters written by different authors. In order to enhance the clarity of each section, these authors were left to express themselves freely, in line with their own personal background and skill areas. Certain redundancies, or nuances of *meaning, can therefore be seen in the different chapters, which in no way compromise the overall coherency of the study.*

The Air and Space Academy trusts that this work will assist decision makers in determining the steps that must be taken, within the possibilities offered by automation, to pave the way for a safer, more efficient global air transport system.

Anne-Marie Mainguy

President of the Air and Space Academy (AAE)

0 PREFACE AND EXECUTIVE SUMMARY

0.1 Preface

Authors: Alain GARCIA et Daniel DEVILLER

During the second half of the 20th century, commercial air transport made huge strides thanks to steady improvements in affordability, efficiency and safety. This progress came about mainly through technological innovation and training, changes to operations and air traffic control, aided by a high level of investment made possible by political support for this mode of passenger transport. During this period, there was plenty of scope for investigation and innovation. However, with the achievement of a high maturity level and the impact of a global economy, constraints weighing on the air transport economic sector increased in number and severity.

Mindful of the challenges facing this sector in the future, in 2009 the Air and Space Academy (AAE) launched a study to identify the main issues within a 2050 framework and to put forward solutions, keeping in mind that flight safety remains an essential goal.

AAE first set about defining the major societal issues facing air transport between now and 2050. Dossier No.38*, published in 2013 and entitled "Flying in 2050", outlines a vision and puts forward recommendations.*

The ambit of the analysis was then expanded so as to examine past and future tendencies in specific areas seen as having the potential to deliver further improvements in air transport operations within this timeline. Among these, automation and connectivity were selected as being of vital importance:

- *automation has already played a significant role in improving air transport efficiency and still has a role to play, as long as the specific possibilities and limitations of human action are taken into account;*
- *connectivity has an essential role to play for liaison purposes and it is vital that data transmission be reliable, efficient and secure.*

This dossier presents the findings of these studies.

On the basis of ambitious goals for improved flight safety, the study group's aim was to map the essential conditions for the global, coherent, optimised use of automation[1] – with the necessary connectivity – in air transport. The group bore in mind possible and probable technological developments and increased knowledge of human capabilities, particularly in terms of cognitive capacity. It focused on flight management, mainly onboard, taking into account the essential factor of the human-machine relationship. It concentrated on principles for the design, operation and organisation of the major operating components of the air transport system.

The application in practice of these principles required an analysis of risks and a new distribution of tasks, decision-making and potential responsibilities.

Because of the advanced use of automation in drones, findings from this sphere were analysed in order to identify strengths transferable to commercial aircraft.

Lastly, the study looked at the many research initiatives already underway to assess their comprehensiveness and to encourage close coordination between research and industry players, and in order to provide solutions for the innovative, effective, safe development of these automated systems.

Because of difficulties in accessing comprehensive economic cost-/benefit data, there was no analysis of the economic repercussions of the proposals, despite their being essential criteria in any decision. Freed from such constraints, the study was able to concentrate on technically feasible solutions. AAE therefore restricted the scope of this study to recommendations that are technical and certifiable[2], upon certain conditions being met, and left it up to the economic players involved to initiate their own coordinated analyses.

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1 *At this stage, it was decided to study increasing automation without referring to the basic conditions for creating autonomy. Autonomy can be defined here as the capacity of an aircraft to carry out a mission fully independently. It is emerging that automation will enable such a feat for missions with broader and broader perimeters. This "Increasing Autonomy" is achieved by the use of more and more sophisticated automated systems. These are the object of the study in the constitution of automats and robots.*

2 *The approach to automation used here is linked to identification in Annex 2 of the goals for reliability needed to ensure the "certifiable" level. Due to the risks of cyber-attack, the effects of which could be disastrous with increased autonomy controlled by more and more powerful autonomous systems, strict precautions will need to be taken both in terms of design and airline operations.*

The intention, then, was to produce an evolving vision of the future, identifying possible steps on the path to increased automation and the impact these would have on the roles and responsibilities of air transport players. The approach thus formulated could identify the necessary conditions for implementation of automation on a material, human and organisational level. The study concludes with recommendations addressed to the various stakeholders (only touching briefly on the question of how to prepare passengers for more highly automated flight).

Table 1 illustrates the possible stages (or scenarios) for evolution. Given a logical progression towards increased automation, it reveals how the function of pilot, at the very heart of air transport, could be affected.

Scenarios / Pilotes	Scenario 1	Scenario 2a	Scenario 2b	Scenario 3	Scenario 4	Scenario 5a	Scenario 5b
Onboard pilot (OP)	**As today, with extension of flight automation**	**Long-haul (LH):** 2 OPs on takeoff, approach/ landing; Single pilot in cruise (SPC) **(no 3rd OP)**	**Long-haul (LH):** 2 OPs on takeoff, approach/ landing; Single pilot in cruise (SPC) **(no 3rd OP)**	**Short-/ medium-haul (S/ MH):** 1 OP with diversion airport less than X mins away	**1 OP for short- to long-haul** In cruise, for LH, when OP at rest GP takes over control of aircraft	**1 OP for short- to long-haul** OP resting during cruise flight in LH	**No OP** (Role of captain to be determined)
Ground pilot (GP)	**GP** not necessary	**GP monitoring during cruise flight.** Reaction time for effective resumption of control =10 mins)	**No GP**	**GP monitors whole flight** in S/ MH (reaction time = 10 min)	**GP for all flights (~10 min** reaction time, but 2 mins when OP is at rest)	**No GP**	**GP for all flights** (rest by means of 2nd GP for LH)

This dossier draws on the presentations and discussions that took place at the international conference organised by AAE on 1-2 June 2016 in Toulouse entitled "Will air transport be fully automated by 2050?"; material was also used from the following AAE conferences: "Aircraft and ATM Automation" (2005), and "Air transport pilots facing the unexpected" (2011), summarised in AAE Dossier No.37*.*

The various authors will be given at the beginning of each chapter[3]. Annex 1 summarises these contributions and Annex 2 summarises the main effects of the scenarios on the most important air transport functions.

3 For more details, please contact them directly.

0.2 Executive summary

Note: The following essential recommendations and summarised presentation are drawn up for the attention of all persons required to decide on actions and investments in direct and indirect activities of research, development, operation and regulation of the civil aeronautics sector.

At this stage the recommendations are not directed at any specific group in particular so as to provide an overview, from which to select relevant contributions and even propose shared ones. More specific recommendations for certain branches will be found throughout the text, and particularly in chapter 9.

0.2.1 Key recommendations

► ***Key Recommendation 1***

Extend automation and connectivity to improve safety.

In latest-generation aircraft which are more automated than those of preceding generations, the rate of fatal accidents has improved appreciably. However, the curve is now levelling off. Greater automation to assist humans (who currently represent 50 % of accident cause factors), combined with robust communications, will help maintain the average number of fatal accidents per year at its current level within a 2050 timeline, notwithstanding traffic growth. Safety improvement goals must be targeted.

► ***Key Recommendation 2***

Introduce new, essential functions.

- *Introduction of a recovery mode that returns the aircraft to safe flight conditions, as practised in military aviation.*
- *Real-time transmission onboard of enhanced weather forecasts.*
- *Real-time transmission to the ground of flight data, as often as is required by the situation.*
- *In-flight monitoring of the pilot's state of vigilance and possible incapacitation by means of new resources.*

► *Key Recommendation 3*

Assimilate human possibilities and limitations into the design and development of a new set of integrated functions.

- *The human-machine interface must take account of the cognitive and physio-psychological limits of humans, in line with scientific studies.*
- *Situations must be depicted in such a way as to be permanently intelligible, by means of relevant, intuitive information, so as to avoid any "cliff effect" in the event of exceptional situations (multiple changes causing a steep increase in the pilot's brain activity, such as a multitude of failure alarms – "Christmas lights" – on the Flight director).*

► *Key Recommendation 4*

Maintain at least one pilot onboard commercial passenger aircraft until 2050.

- *Human intervention will remain necessary to deal with unforeseen events, as is the case today, since automation will not be capable of dealing with all cases and all decisions.*
- *In 2050, the single onboard pilot will be supported by a powerful robotic capability (computing capacity) and the assistance of a ground pilot to compensate for their failures.*
- *Testing of future automated systems will cover a sufficient number of exceptional cases, based on in-depth experience.*
- *"Autonomy" will progressively be introduced, in stages that vary with the type of mission, whenever players see a potential economic gain.*

► *Key Recommendation 5*

Deliver design, development and validation means in line with the complexity of the overall system (associated aircraft/external systems).

These resources, methods and tools will need to be more sophisticated than at present in order to ensure optimal detection of failures, with comprehensive tests covering foreseeable, though exceptional, cases and even beginning to tackle "unforeseeable" events.

► *Key Recommendation 6*

Manage impact on air transport components other than aircraft.

- *Enable airlines to adapt to new modes of operation, including flight monitoring and the role of the ground pilot.*
- *Adapt procedures, organisation and ATM to this enhanced automation and connectivity.*
- *Allocate frequencies and provide robust means of communication to enable flight monitoring and resumption of control by the ground when necessary.*
- *Train staff to understand the functioning of these more highly integrated systems and to react safely to unexpected situations (basic airmanship).*

► *Key Recommendation 7*

Improve R&D coordination between players.

- *Pursue research efforts to achieve set goals, within the framework of priorities indicated above.*
- *Research organisations and industry have moved forward on these subjects but coordination must be improved, despite the handicap of confidentiality.*
- *The drone industry is working towards a high level of autonomy. Its findings should be taken into account and dual uses considered.*

0.2.2 Presentation / Summary

Author: Alain GARCIA (AAE)

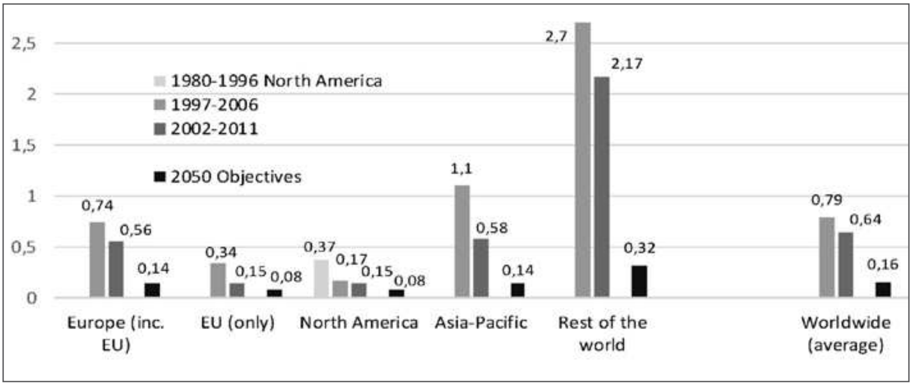
CHAPTER 1

*This chapter pertains to "**Current safety level and goals for improvement**":*

The rate of fatal accidents per flight has been falling steadily in recent decades but is now levelling off. However, given forecast traffic growth, the accident rate will have to be cut by a factor of four worldwide (cf. AAE Dossier No.38*) simply to avoid a rise in the absolute number of accidents. To achieve this, separate goals would have to be set for different areas of the world given variations in current rates. The following figure (page 28) gives an example of these.*

These differentiated goals could be implemented internationally by ICAO with the aid of EASA and FAA.

Increased automation will accompany state-of-the-art innovations introduced into latest generation aircraft, assisting humans and making them more reliable. With



Number of fatal accidents per million flights.

humans linked to 50 % of primary causes of accidents (75 % 20 years ago), this should play a decisive role in bringing the accident rate down.

An analysis carried out into the circumstances of each accident brought to light four main families: losses of control, collisions with the ground, runway excursions during landing, and unexplained cases. This approach is already used by international thinktanks working towards greater flight safety, with measures already being taken in the areas of cockpit design and crew training. But with a high number of unexplained cases still remaining, automatic flight data transmission is strongly recommended in the event of any anomaly, regardless of the aircraft's geographical situation.

CHAPTER 2

*Having identified these goals, AAE decided to look into how automation was progressively introduced into air transport in order to reveal any benefits and difficulties encountered. This is the aim of chapter 2, entitled "**Some considerations on automated systems and their history"**, which concludes as follows:*

"Transformed by the new availability and sophistication of microcomputers, avionics now play a leading role in flight control. Likewise, far-reaching changes have been introduced into computer system architectures, including digital multiplexing and local area networks (LAN), optoelectronics, massively parallel computing and new neuronal techniques now available to cognitive engineers."

The role of humans in the "aircraft system" has evolved as a result. For the moment at least, humans act at a higher level of intelligence and intuition than machines, though the form of intelligence known as "artificial" is rapidly closing in on our own. The art of piloting a commercial aircraft has thus shifted gradually but fundamentally away from basic initial training. Training in airmanship retains its specificity and still reflects the vocational aspect of the pilot's profession. However, the skills required are very different now, and more demanding in terms of scientific and technical knowledge.

Design is therefore likely to be reoriented with a view to:

- *on the one hand, harmonising and merging the skillsets of new pilots into more and more highly automated aircraft functions;*
- *on the other,* ***restricting human intervention, although necessary, to the increasingly rare occurrences of unexpected and dangerous situations.***

When the likelihood of an accident is low enough, it will be time to entertain the idea of eliminating the onboard pilot. But not for the moment!

Indeed ***"...although less and less tied to the control stick, pilots are still irreplaceable for managing the thousand mishaps and incidents encountered each flight which could degenerate into catastrophe."***

CHAPTER 3

*Chapter 3: "**Basic theory of automatic flight control**" presents a methodical approach to automation of flight control. The concept of piloting is taken as representing the highest level of tactical, strategic decisions governing actions applied to the aircraft's flight control surfaces. In this approach, the different piloting modes are identified and sorted into a hierarchy, resulting in a strict architecture for automation. The human/machine relationship within the flight control loop is analysed and the demands on interfaces clarified. The concept of crew is extended to include all players, including automated systems and the ground.* ***The purpose of automation cannot be to eliminate the human operator. In-depth study shows that humans and machines are indissociable. Consequently, human and machine, onboard, must form a crew****. The complete crew already includes one or more parties on the ground, a tendency that will only increase. It will eventually become technically possible for a complete transport mission (a "meta-mission") to be performed by robot substitutes sufficiently autonomous to ensure the return trip even in the event of re-routing (some military prototypes are already capable of this). But this will not lead to the human operator being eliminated. Rather it will call for a redefinition of the functions and competences of each and an ensuing adaptation of the instrument panel and the processes of selection and training.*

The strict hierarchical structuring of the system will see the mixed human/machine loop giving way to a hierarchy of "loops" of increasing intelligence levels, in which the human loop is reserved for judgement and decision functions the machine is incapable of (falling outside of the realms of programming). These technical possibilities will impact crew management.

The following recommendations are made:

- ***Priority must be given to developing the vital preventive role of automation over its less successful, remedial role****. It is advisable therefore to put maximum emphasise on prevention in order to minimise the likelihood of cases of incapacitation.*

- *It would be wise to first build a more reliable, minimal system, that allows resumption of control in critical situations and recovery mode.*
- *In the very long term, the fully automated aircraft will be a robot, capable of carrying out the recurring tasks of an entire mission.* ***It will nonetheless remain under the control of an onboard human operator, who will manage un-programmed (unforeseen) situations with the help of appropriate controls. Automated systems contribute to safety and crisis management****. This configuration, expected in several decades, will be the result of a "cybernetic transition". A vast development programme should be launched, including demonstrators for automated systems, in order to achieve this robot.*

CHAPTER 4

*This theoretical approach is followed by a study based specifically on knowledge of human behaviour, not only in terms of cognitive capabilities but also physio-psychological limits. This is the subject matter of chapter 4 with its deliberately provocative title: "****Are pilots necessary onboard?****" The daily actions carried out by pilots to ensure safe flight were studied. Mainly they are prompted by unforeseen events (or modifications due to airline imperatives) which cannot be comprehensively known to systems designers and are therefore impossible to anticipate in flight control software development. (Moreover, it is considered that "all event" safe modes will not have been designed and tested within the timeline we are concerned with). This led to the following conclusions:*

In 2050, and even beyond, there will still be at least one pilot on board.

*The evolution towards greater autonomy in flight (*i.e. automated systems controlling flight without any outside intervention unless prearranged*) is inevitable, but will only be possible on condition that we:*

- *leave pilots do whatever they can do better than automation, particularly in unexpected or unforeseen situations;*
- *take human capacities and limitations into account in any pilot-aircraft combination, to ensure successful integration with the automated systems-prostheses designed to increase the effectiveness of the duo;*
- *provide pilots permanently, wherever they may be, with an accurate perception of any situation, which means reviewing the nature of the information they receive as well as the means to send it.*
- *avoid any "cliff effect" in emergency failure situations;*
- *do not cancel protections in degraded flight modes or after involuntary departure from the normal flight envelope;*
- *select and train pilots in self-control, risk assessment, basic airmanship, recovery after flying outside the flight envelope;*
- *solve the problem of vigilance.*

The evolution towards greater autonomy is focusing reflexions on the single onboard pilot configuration, particularly for economic reasons (yet to be proven by airlines).

In-depth, detailed study of this configuration reveals the need for complementary human assistance on the ground, ***as well as a degree of aircraft autonomy in certain circumstances****, in order to ensure an acceptable accident rate. These constraints argue for a clear definition of the advantages and disadvantages (in terms of safety, efficiency, new means, training and costs) of abandoning the two-member crew, a configuration which could be appreciably improved, and a careful step by step approach to implementation of the single pilot configuration.*

Total autonomy, i.e. no onboard pilot, cannot, on the contrary, be envisaged in a 2050 timeline and is not recommended in safety terms. Partial automation will though be possible in certain specified cases and conditions, and will gradually be introduced.

*One difficulty is underlined however: "*Given the interactions and interconnections between systems ensuring this autonomy, the combinations of possible cases envisaged will become more and more difficult to monitor, calling for increasingly complex software and raising the risk of unforeseeable knock-on effects*".*

Analysis of scenarios: *the considerations outlined in previous chapters enabled us to analyse the scenarios defined above in order to identify their implementation requirements. This analysis is summarised in the table contained in Annex 2.*

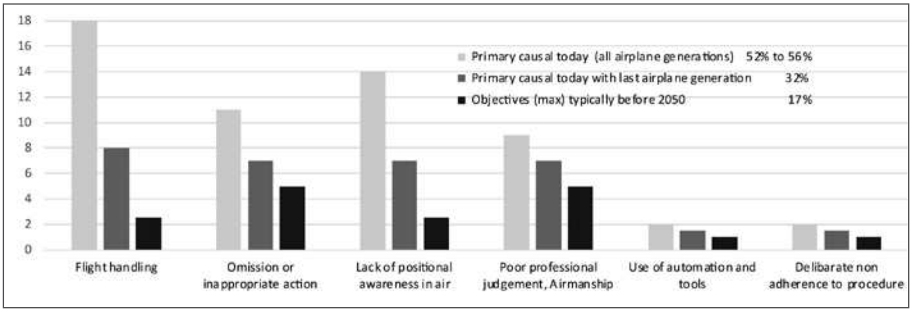
CHAPTER 5

"Analytical approach to evolutions in flight control within a 2050 timeline"*, puts forward two analyses based on* ***quantitative information*** *collected during commercial flights. The first tackles potential safety gains in flight control within a few decades for 2-pilot onboard crews; the second looks into aspects conditioning the move towards flight control by a single onboard pilot with assistance from the ground.*

The first analysis, i.e. flight control by two-pilot onboard crews, as today, *is summarised on the figure hereafter, which shows:*

- *the occurrence percentage of the main types of human failure as primary cause factors in fatal accidents in the years 2002-2011;*
- *improvements already observed in latest generation (already relatively recent) aircraft in the same period;*
- *realistic goals to reduce the impact of each type on the accident rate by 2050 (an engineering assessment).*

The second analysis, i.e. flight safety within the context of a single onboard pilot assisted by a ground pilot, aims to identify the necessary characteristics and performance of backup and substitution systems. The choice of onboard systems, as well as the ground assistance to set in place via suitable means of communication,



Primary causes of air accidents and targets.

is broadly informed by the different kinds of physiological – and psychological – dysfunction seen in pilots, and their occurrence rate. Partial losses of capability, for instance, difficult for onboard systems to detect, would appear to be the most critical from a safety point of view, if they are not declared by the pilots themselves.

Based on hypotheses and data from operational flights, it is shown that:

- *the onboard pilot should typically receive continuous assistance from the ground pilot, with a communication delay of < ~1 second, during takeoff and initial climb as well as final approach and landing phases;*
- *the ground pilot should monitor the situation for 1 to 2 minutes every 15 min in final climb and descent phases and every 30 min in cruising flight. During these phases, ground assistance should also be provided if any external threats to the cockpit have been reported.*

The best compromise must always be reached between safety and operational efficiency, with flight monitoring by ground pilots assigned either according to geographical area (thus placing the accent on knowledge of the environment), or flight (thus placing the accent on knowledge of the onboard pilot and aircraft resources). The estimated assignment rate could vary, on average, between 5 and 8 flights per ground pilot.

In order to consolidate these preliminary analyses, pilot performance reports and in-flight experiments should be pursued and extended, and should even include autonomous flight.

Any economic analysis of this potential evolution towards a single onboard pilot must also assess the efficiency of the various options for ground support organisation.

CHAPTER 6

*AAE considers that the designers and operators of future, more automatic aircraft, leading to more or less automated flight phases, should make use of experience gained through drone development and operations. Chapter 6, therefore, reviews the **"Contribution of feedback from drones"**.*

*Current drone solutions would of course have to be improved, if they are to achieve the targeted safety requirements for air transport. The military will clearly be highly motivated to make progress in this respect, and it is easy to imagine the emergence of many dual-use technologies. The drone sector i**s currently exploding and, as enablers of innovative technological solutions**, UAVs provide an ideal basis for pre-development of future automated systems. **Commercial aircraft manufacturers would be advised to keep abreast of such evolutions with a view to implementing them in their own activity.***

Drone-specific operational regulations could also provide a model for even partially autonomous aircraft in certain sectors such as general aviation.

In time, the initial gap between civil/military drones and commercial aviation will close and joint research and development will emerge, although it will probably not be mature before 2050.

CHAPTER 7

It is important to look beyond aircraft and flight control to examine the air transport environment as a whole, which will also be more interconnected and more highly automated. Chapter 7 considers those entities and aspects impacting and impacted by connected aircraft. These are:

a) Airlines:

We must consider the main effects of such changes on the functioning and organisation of airlines, as well as possible impacts on current trades profiles.

Some initial considerations:

- *The exercise of authority onboard aircraft:*

  *When envisaging a single onboard pilot, **it is vital to ensure that they will have the mental and physical availability during the entire flight to carry out the mission**. And to clearly define who, of the cabin crew or ground support, will assist or cover for them and even take on some of their responsibilities.*

- *Creation of the "ground pilot" function.*

  Scenarios involving a reduction in the number of pilots on board always entail the creation of a technical ground support, capable of covering for the pilot in the event of incapacitation. These "ground pilots" will most likely be seasoned pilots who have passed a specific additional training module. These pilots will alternate periods on the ground and periods in the air to maintain their qualification and flight experience.
  Airlines' flight operations will need to be reorganised accordingly.

- *The role of Operations Control Centres and operational communication:*

  The OCC, an operational nerve centre for coordinating and monitoring airlines' flight schedules, is currently the only point of contact between pilots and airlines during flight. A clear definition will need to be given of the roles of the OCC and *the ground pilot in all exchanges with the aircraft. The ground pilot will have to be in close proximity (in both geographic and communicational terms) to the OCC and will work in close collaboration.*

- *Commercial communication*

  The use of communication services for passengers will need to be regulated to prevent them from becoming a source of distraction or disturbance.

b) Air Traffic Management – ATM

Although the intrinsic functions of ATM will not alter, the evolution will concern ***trajectories*** *and a greater pooling of information between players, supported by SWIM (System Wide Information Management), to enable* ***collaborative decision making*** *and thus improve performance. Different scenarios must be studied for role distribution.*

This exchange of information between more connected, automated aircraft and ground systems will affect ATM organisation. This could result in a severing of the geographic link between air traffic controllers and their area of responsibility, as long as appropriate data link is available, and might entail delegation of separation management to the onboard pilot or automated systems.

Automatic systems will be developed onboard as well as systems to assist the ground operator in order to contend with unmanned passenger aircraft. New automated systems for trajectory management, anti-collision management, operation enhancement over airports and air-ground data-link applications will contribute to this evolution in ATM.

In-depth study must go into elaborating ATM procedures to improve, facilitate and even automate the use of onboard automated systems, and to accept aircraft with different capacities within the same airspace.

c) Communications

More automated, connected aviation is entirely dependent on spectrum resources and secure communications. Clearly the specific needs of connected aircraft will require much greater bandwidths than today. ***This problem of spectrum availability is therefore critical****, especially since aviation lacks weight compared with other sectors in the competition for access to the spectrum.*

Safety goals result in a segregation between regulated services (ATM) and non-regulated services. For the latter it is possible to fall back on standard solutions from the wider world. In the case of commercial aviation, particularly in dense airspace, very high demands are made on communication means (latency, capacity, security, availability), directly linked to flight safety. There is no single optimal solution, but the number of different technologies is restricted by the need for systems interoperability.

The system must be capable of resisting all types of interference. While safety is paramount, cybersecurity is equally so.

Much work remains to be done to lay down detailed procedures for single-pilot operations with a remote ground pilot, to redefine the roles and responsibilities of the various players, to elaborate regulatory requirements and to identify needs in terms of communications (bandwidth and performance).

d) Aviation meteorology

Knowledge on weather conditions is vital for accurately predicting trajectory – thus anticipating the risk of separation loss between aircraft – and for foreseeing unfavourable flight conditions likely to cause pilots to modify their flight path. But major areas of uncertainty still exist in certain meteorological situations that are either difficult to forecast or very short-term. The characteristics of the atmosphere remain chaotic and no error model is valid all the time. Atmospheric observations, and as a result weather forecasting, have considerably improved due to major technological innovation and extensive research. Having said this, whatever the quality of weather data, ***what is important is its integration into air transport systems****. Different scenarios can be envisaged going as far as to translate data into impact, with a system analysis that proposes optimal solutions to the operator. The formatting of weather data is therefore a crucial aspect since it must be shared in a compatible form.*

The SWIM networks services make this data available, but responsibity for its use is not specified. ***The roles of the different players – weather services, OCCs, crew and ATM – remain unclear.***

e) Personnel training

As aircraft become more and more autonomous, the pilot's task will consist essentially of flight management: automated systems will be charged with ensuring safety by keeping the aircraft within the flight envelope, with the pilot monitoring the situation and resuming control if necessary.

Pilot training will gradually move from knowledge-based to skill-based learning, and this will have to be taken fully into account in the selection process. Given such a far-reaching evolution, a robust transition plan must be drawn up early on, without waiting to complete the experimental and system development stages. In order to do so, the role of the different players will have to be defined in detail.

But the true challenge will lie in the pilots' ability to understand why and how the system reacts. The greater a aircraft's level of automation, the more complex its functioning will appear. ***The system will need to be presented to humans with a minimal level of intelligibility, skilfully concealing a complexity which already exceeds human cognitive capacities at any given time****: the analysis of complex situations will have to be simplified and training in reacting to the unexpected will become mandatory.* ***As it is impossible to foresee all unexpected cases, the aim should rather be to instill appropriate behaviour in the face of a new situation, using basic principles of airmanship.***

To meet this challenge, training specialities should be decompartmentalised and multidisciplinary programmes encouraged.

f) Legal framework

Will the major technological changes expected within a 2050 timeline call for changes to legislation? *Not necessarily. The international conventions governing air carriers' responsibilities do not define what an aircraft is, and could therefore be applicable to unmanned aircraft as well as to conventional aircraft. A fortiori, the introduction of passenger or freight aircraft by 2050 with a single pilot onboard plus a ground pilot timeline will require no modification of current international conventions. There will, though, be a new focus of responsibility on the carrier, which will be fully liable for any damages, in accordance with its technical responsibilities within this new framework (increased risk of cyberattacks).*

CHAPTER 8

In order to enable the desired changes described above, new, innovative solutions must be developed which will push back current limitations. Chapter 8 describes the study and development areas seen as priorities by AAE, and ***the related upstream research areas. Ongoing research presented at the June 2016 conference will also be presented.***

The study and development areas identified focus on:

- *flight control automation and enhancement of pilots' capacities for intervention: ensuring sustained attention and improving transition between automatic modes and manual resumption in the event of unforeseen events (including new display techniques to facilitate interpretation of alerts);*
- *extension of flight envelope protections and detection of dangerous behaviour or actions on the part of the pilot;*
- *incorporation of the probabilities associated with meteorological events to improve ATM;*
- *new role distribution between aircraft and ground and functional command of the growing complexity of the air transport system;*
- *full control over the industrial development of complex systems (from design to certification);*
- *extension of new role distribution between air and ground to flight control with a single pilot onboard;*
- *more and more autonomous flight control.*

The major European manufacturers such as Airbus, Dassault Aviation and Thalès have provided examples of developments currently being carried out on own or private-public funding.

Upstream research areas for prioritised studies and developments include:

- *understanding human behaviour and the role of the onboard pilot, particularly in the different situations encountered in the cockpit (unforeseen events, fatigue, stress…);*

- *a general approach to role distribution between humans and machines in order to optimise overall performance and determine the question of authority;*
- *developing the human-machine interface by setting in place tools and solutions to optimise information perception and active assistance to pilot attention;*
- *assessment methods of the "human-system" duo and the engineering of human-machine interactions;*
- *integrated engineering for air transport systems;*
- *control over development of embedded systems and software, systems resilience.*

Chapter 8 cites ENAC, ISAE, Meteo-France, ONERA, ENAC, NLR, FIT, NASA, NTSB and the United Technology Research Center as organisations working on these topics.

*It would appear that **many excellent initiatives are being adopted** by both industry and State and private research organisations, with relevant, far-reaching topics. But the prevalent feeling is that **these would be more efficient if an organisation were to be set up to establish closer relations between aeronautics players** as well as with other fields of application (such as the automobile industry). For example, **demonstrator or development projects in the desired direction involving complementarities could constitute a foundation for tasksharing, with the help of financial incentives. The sacrosanct principle of confidentiality (for the protection of intellectual property), often used as a brake, should in this case be used with discernment.***

CHAPTER 9

Chapter 9 summarises the conditions and recommendations to be met in order in order to successfully negotiate the series of stages relating to the different types of "operational" crew composition.

These recommendations focus on:

- *prioritising human aspects, rationalising and extending automation to make it easier for humans to understand, by providing relevant information at all times and by taking into account normal and abnormal modes of the human brain;*
- *closer co-operation between neuro-specialists, designers and users;*
- *compliance with the principle of decisions being taken by humans and executed by the machine, which can propose actions appropriate to the situation;*
- *improved utilisation of modern technologies to collect and analyse large amounts of data, including information on the handling of everyday, nonnominal situations by pilots;*
- *an evolution in cockpit design, with display of solutions in the event of any problem and goal-based control;*
- *the introduction of a recovery mode and, of course, the generalisation of automatic collision avoidance functions;*
- *the collection of flight data with sufficient regularity for the flight underway;*

- *the transmission of weather forecasts in real time to the aircraft, enhanced by merging sources and information from other aircraft;*
- *control of the development and validation of these new, more complex, broadly integrated systems, at least functionally, by way of new means to detect defects and ensure comprehensiveness of tests covering exceptional cases that are foreseeable;*
- *the development of global simulation centres by interconnecting specialised centres;*
- *for long-haul flights, which are more exposed to risks related to the duration of the mission such as loss of vigilance, provision of all necessary means to monitor the state of the pilot flying and availability of effective communications;*
- *for a crew reduced to a single onboard pilot, provision of reliable means to detect any incapacitation;*
- *adaptation of airlines' functional organisation due to increased intervention in flight control from the ground (OCC, presence of the pilots on the ground);*
- *for air traffic control, the development of technical means to reduce the workload of the crew.*

1 CURRENT SAFETY LEVEL AND GOALS FOR IMPROVEMENT

Authors: Jean BROQUET and Xavier CHAMPION

(For the validation of the values taken into account see note on page 52)

1.1 Changing numbers of fatal accidents in recent decades

Figure 1 shows the number of fatal accidents per million flights (three-year average) for commercial air transport, from 1992 to 2013.

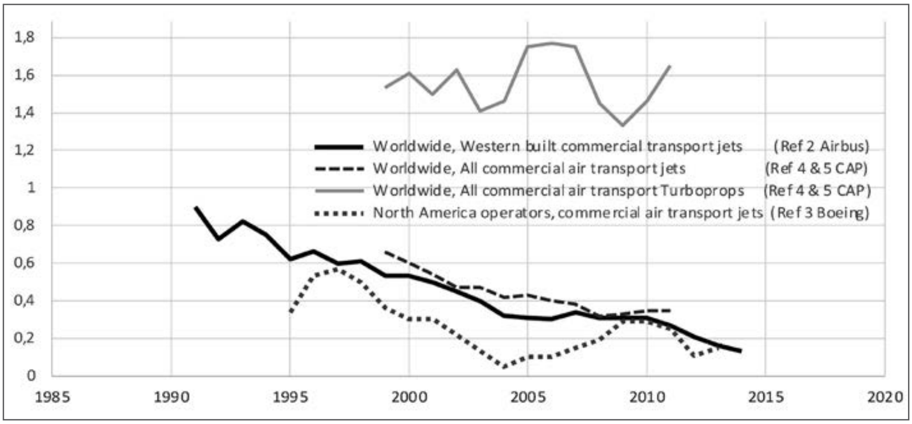


Figure 1: Evolution in the number of fatal accidents.

The rate of fatal accidents for jet aircraft between 2002 and 2011 was approximately 0.37 per million flights (or 0.37 x 10^{-6}/flights), for a total of 248 million flights and an *average flight time of around 2 hours. For Western-designed jets, this rate was ~ 0.30 per million flights.*

Turboprops registered a total of 70 million flights with an average flight length of ~ 0.9 hours and a fatality rate of 1.6 per million flights.

The fatal accident rate for North American airlines (and EU carriers) was approximately 0.16 per million flights.

The average rate of fatal accidents worldwide over the decade 2002-2011 for commercial transport, including jets and turboprops, is thus negatively impacted by turboprops, and stands at approximately 0.64 per million flights (aircraft over 5.7 tonnes, not limited to those of Western design).

1.2 Fatal accident reduction targets by 2050

Air and Space Academy Dossier 38 (ref. 1) made the following recommendation concerning flight safety:

"It is imperative to set a worldwide goal to improve safety by a factor of four by 2050 as compared with the 2009 level, with no continent having a safety level under half the global average."

Figure 2 gives the number of fatal accidents per million flights for commercial passenger and cargo aircraft - jets and turboprops - over 5,700 kg, in various areas of the world (airlines' centres of operations), for the periods 1997-2006 and 2002-2011 (values drawn from refs. 5 and 6).

Based on AAE forecasts for world traffic distribution by 2050, it indicates the goals to be achieved by 2050 in the different geographical areas to obtain an average overall accident rate of 0.16 per million flights (i.e. a quarter of 0.64 per million flights), whilst meeting the further condition that no continent should have a safety level less than half the world average.

Note: Given, on the one hand, differences in the regional perimeters of the accident and traffic evolution statistics provided and, on the other, the diversity of situations in the areas grouped into "Rest of the world", the rates indicated in this category are rough averages that do not represent the accident rate of a country or an area in particular.

The aim of improving the safety level by a ratio of two (see Figure 2) in North America and the EU, i.e. reducing the fatal accident rate from 0.15×10^{-6} to 0.08×10^{-6} per flight, will not be achieved simply by integrating equipment and procedures elaborated for latest generation aircraft. (The fatal accident rate for the decade from 2004 to 2014, for example, for Western-design, last-generation jets, still remains at 0.11×10^{-6}/flight.)

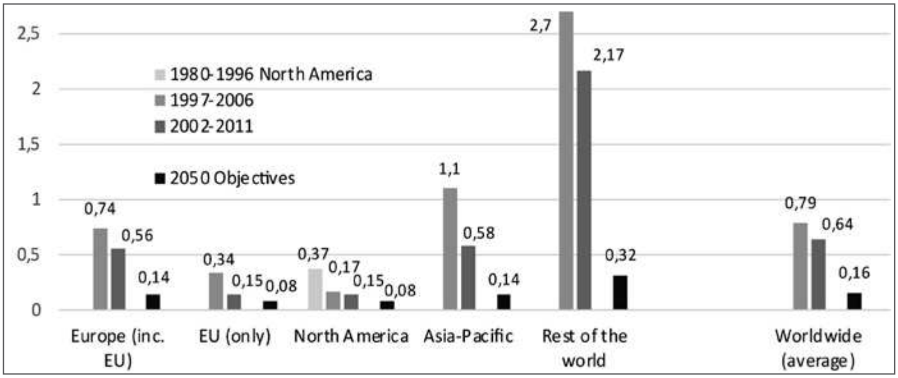


Figure 2: Number of fatal accidents per million flights.

Improvements in Europe (outside EU), Asia-Pacific and the "Rest of the world" will come partly from the replacement of old generation aircraft. They will also come from optimal use of present and future experience gained in North America and the EU, with all necessary adaptation to suit the specific culture of each country.

1.3 Aircraft handling safety improvement targets for 2050

Flight safety must be enhanced by introducing a number of improvements into onboard and ground equipment, systems, services, operations and procedures, etc., each impacting the accident rate.

This chapter will look specifically at the goal of enhancing handling safety by considering the numbers of fatal accidents that can be put down to related factors.

Figure 3, drawn from the "CAP 1036 Global fatal accidents" report, breaks down primary causal factors in fatal accidents worldwide, over the 2002-2011 period, for all commercial jets and turboprops as well as business jets[4].

Errors on the part of the flight crew (indicated under the term "Airline") are recognised as being the primary causal factor in over 50 % of cases and as main causal factors (primary or significant) in 66 % of cases. This percentage was 76 % (88 % for all main causes) during the 1980-1996 period and 67 % (75 % for main causes) from 1997 to 2006, thus confirming both the continued weight of flight crew errors in average accident rates as well as the absolute and relative improvement trend over the past three decades.

An analysis of accident causes for carriers from the "North America" region over the 2002-2011 period reveals that, while the accident rate is lower, there is still the same

4 *Business jets were not included in the perimeter considered in previous chapters.*

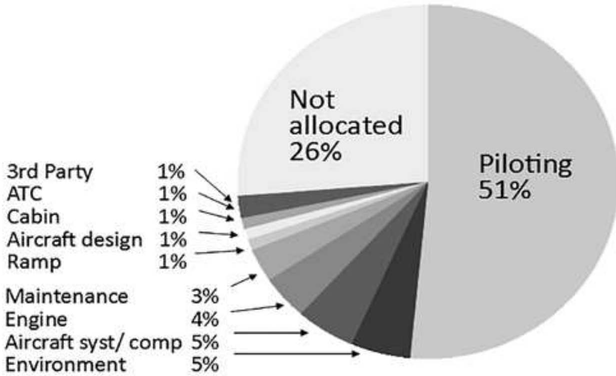


Figure 3: Primary causal factors of fatal accidents.

prevalence of crew errors (50 % of primary causal factors and over 66 % of main causal factors).

It is difficult to define safety improvements for causal factors that are not clearly identified ("not allocated" on the graph) or for the purely weather component of the "environment" causal factor.

The goal of improving flight safety overall by a ratio of two for North American and EU airlines should be obtained through a threefold improvement in all identified causes, in particular those linked to "flight crew errors".

1.4 The specific case of western-made jets: identifying the main ways of improving flight safety

The documents given in reference (Boeing statistics) provide certain indications including a breakdown of accidents according to category by Boeing/CAST and Airbus (Commercial aviation accidents 1959-2014). Accidents occurring during ground manoeuvres are now included and there is in general only one victim per accident; this indicates clearly that the human-machine aspect must be considered in all areas.

For each category, it is necessary to identify causal factors and determine what role is played by human factors;

- *the UK CAA reports ("Global Safety Accident Review", CAP 1036 for the period 2002-2011 and "CAP 776" for the period 1997-2006) analyse the causes;*
- *human error is the primary causal factor for 50 % of fatal accidents in the 2002-2011 period (67 % in the 1997-2006 period);*
- *NB: Ergonomic design was systematically introduced as from the 1990s; the benefits are obvious and such efforts must be pursued;*
- *for each category, the Airbus analysis gives the statistics according to design technology: aircraft are sorted into four generations, the fourth being the most recent (ranking common to Airbus and Boeing).*

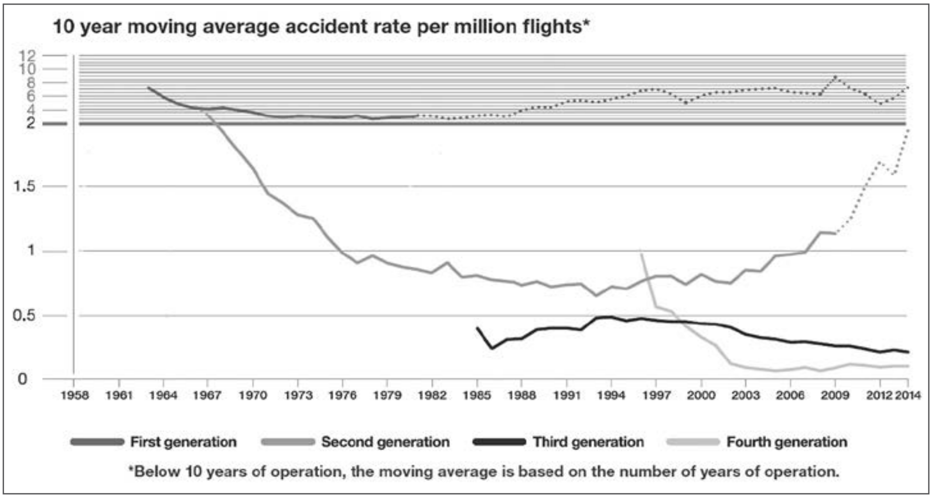


Figure 4: Rate of fatal accidents per million flights according to aircraft generation.

Classification by category

	Number of fatal accidents		Number of fatalities	
	1994-2003	2004-2013	1994-2003	2004-2013
Total	105	72	6795	3906
(LOC-I) Loss of Control in Flight	33	16	2234	1576
(CFIT) Controlled Flight Into Terrain	24	16	1822	804
(RE) Runway Excursion	16	17	192	796
Take-off	3	4	65	38
Ground operations	Unrecorded	7	Unrecorded	8
In-flight collision	2	2	420	156
Fuel tank explosion	2	0	231	0
Runway incursion	3	0	121	0
Non-identified causes	6	3	502	202*

Table 2: Number of accidents and fatalities by category
*(*not including the 327 fatalities of the MH 370 accident).*

This table reveals that:

- *the first three categories still exist, even if significant progress has been made, as shown in figure 5;*

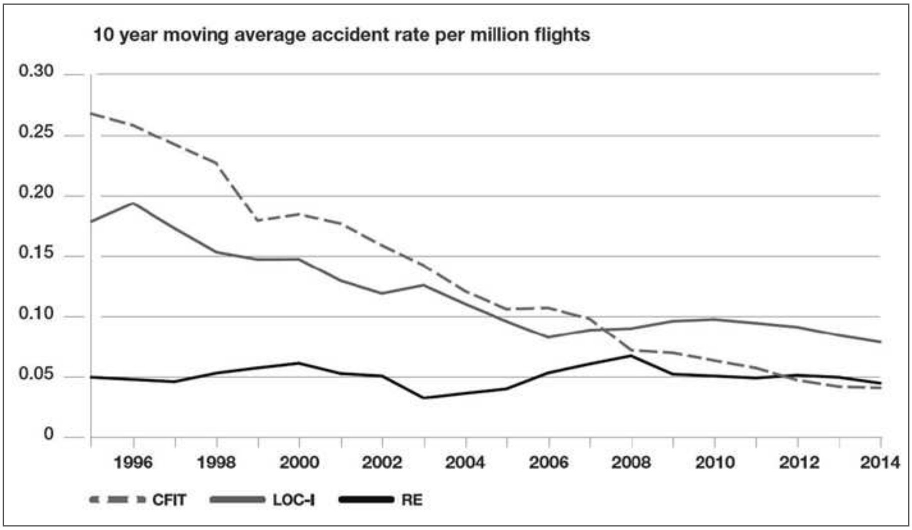


Figure 5: Evolution in numbers of accidents per million flight hours (Airbus).

- *in the fourth category, the number of unexplained accidents remains too high.*

For these four categories, a more detailed analysis has been performed and recommendations formulated (see in the following page).

- ***Loss of Control in Flight (LOC-I)***

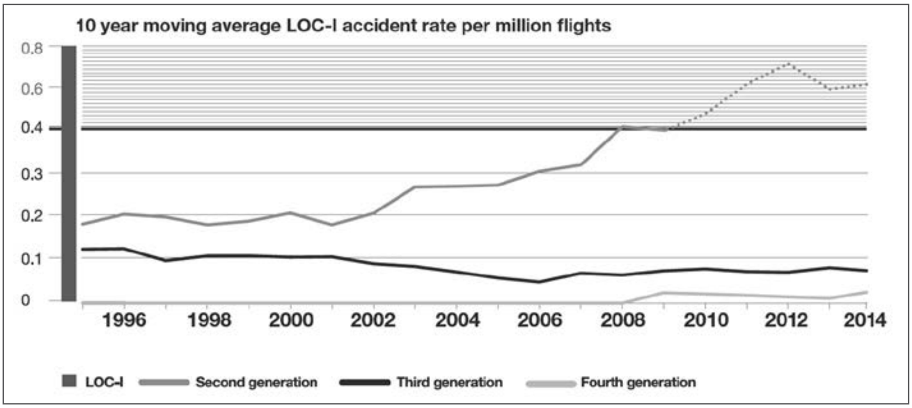


Figure 6: Evolution in numbers of accidents due to loss of control (Airbus).

Human error is the primary causal factor for this category; the CAA has identified five types of error:

- *flight handling;*
- *omission of action/inappropriate action;*
- *lack of positional awareness – in air;*
- *poor professional judgment or airmanship;*
- *deliberate non-adherence to procedures.*

The percentage for each area has not changed, but the absolute number has decreased for third and fourth generation aircraft.

It is vital to continue work in each of these areas; latest generation aircraft are not free from risk, in particular for accidents occurring during cruise phase.

► ***Recommendation 1***

Three lines of action:

- *Decision support: present the situation of the aircraft within the flight envelope when approaching aerodynamic limits in particular: incidence, slip, overspeed.*
- *Lack of positional awareness - in air: automatic switching to recovery mode.*
- *Flight handling; restrict the need for flight crew to regain control in the event of systems breakdowns when the probability is low, i.e. a situation a crew will practically never meet, but which does occur on the level of a fleet. Leave the autopilot activated, even with degraded performance, in the event of a system failure, to allow the flight crew the necessary time for analysis and decision.*

- ***Controlled Flight Into Terrain (CFIT)***

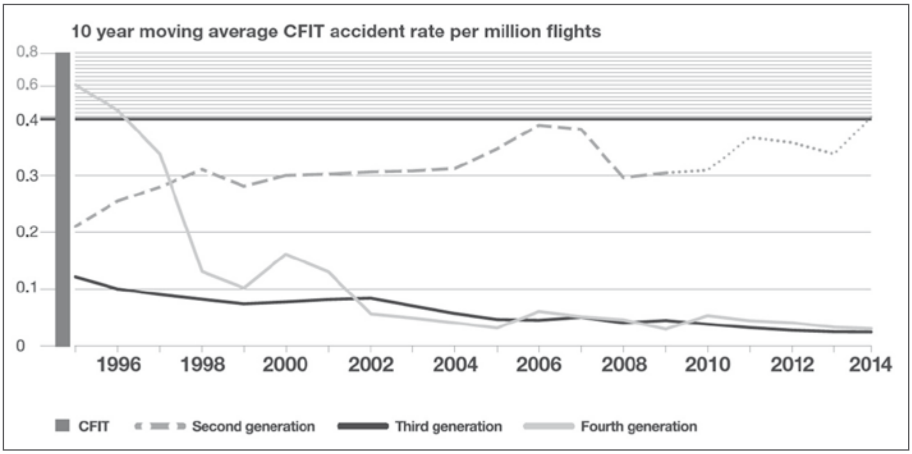


Figure 7: Evolution in accident numbers due to collision with the ground (Airbus).

Figure 7 shows clearly that it is second generation aircraft that are vulnerable to this risk; this category should “disappear” with the phasing out of older fleets. A reduction of one third in the number of fatal accidents can be noted between the two decades considered.

The other cause is non-adherence to procedures, even in the event of a GPWS alarm.

► ***Recommendation 2***

Consider introducing an automatic go-around function in the event of a GPWS alarm (or the new generation, EGPWS alarm).

- ***Runway Excursion (RE)***

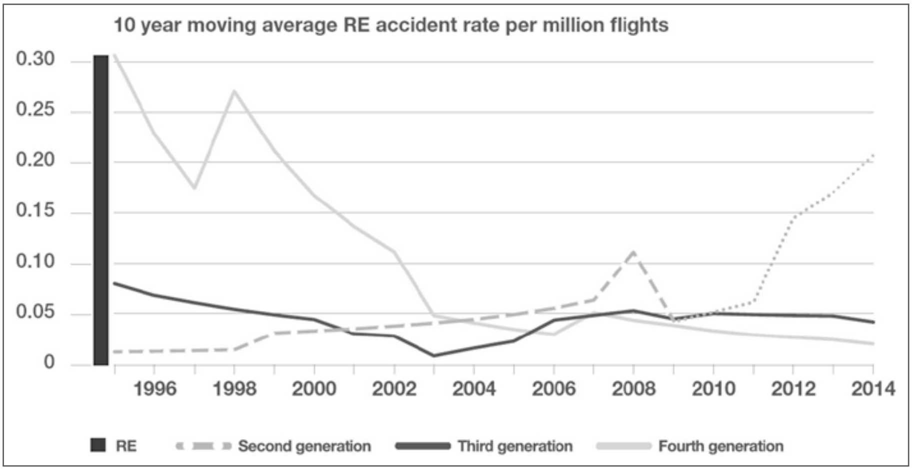


Figure 8: Evolution in accidents numbers due to runway excursion while landing.

Thrust reversers and flaps:

- *the number of high-speed runway excursions has increased, particularly for twin-engine aircraft landings with a defective thrust reverser;*
- *non-extension of flaps is also another primary causal factor.*

► ***Recommendation 3***

- *One possible line of action is to increase the reliability of thrust reversers and flaps, with less than one faulty extension per million flights.*
- *The second approach consists of presenting the energy situation to the crew during approach, i.e. showing them the point of impact envisaged on the runway and the stopping point of the aircraft; this technology has been introduced into aircraft for two years, but it is still too early to measure its effect.*

(It can result in a slight increase in the number of all engines running go-arounds, an operation that does not offer a "good" level of safety for twin-engine aircraft, however this drawback can be mitigated by the introduction of automatic go-around, since the crew workload in a manual go-around is too great to ensure flight path monitoring).

- ***Unexplained accidents***

The number of unexplained accidents remains too high; each accident must be analysed and its causes identified; this requires recovery of data and internal and external exchanges in the last minutes before the crash. The case of flight MH 370 is the best example;

► ***Recommendation 4***

- An automatic, global system of data transmission must rapidly be set up; the tracking system made compulsory by ICAO is a first step and the calendar must be pushed forward for aircraft with a long operating range.

1.5 Important remarks

1.5.1 Validation of analyses from accident statistics used

This dossier is based on documents available in 2013 and 2014 relating to accident statistics of civil transport aircraft. Statistics published since, covering operations up to 2015, show only a very slight evolution in the causes and values for various reasons:

- *an asymptotic trend had already been reached, showing the maturity of the latest aircraft generations, with progressive phasing out of preceding ones;*
- *in order to be valid, accident rates are based on a moving average over 10 years, so a shift of one to two years is not very significant. The same can be said of the values known for operations in 2016. The recommendations resulting from the present analyses are thus shown to be valid.*

1.5.2 On the introduction of new generation aircraft

In his presentation at the conference of 1-2 June 2016, Mike Feary (ref. 8) stressed that close attention had to be paid to transitional stages when introducing new concepts/automated systems. Indeed Airbus data (see figure 9) shows very high accident rates during the introductory phase of each of the four generations of Western designed jets. Although the corresponding number of flights is limited, the absolute number of accidents is significant. Thus, the introduction of fourth generation jets was responsible for an exceptional number of fatal accidents, 15 in all, over six years between 1989 and 1996.

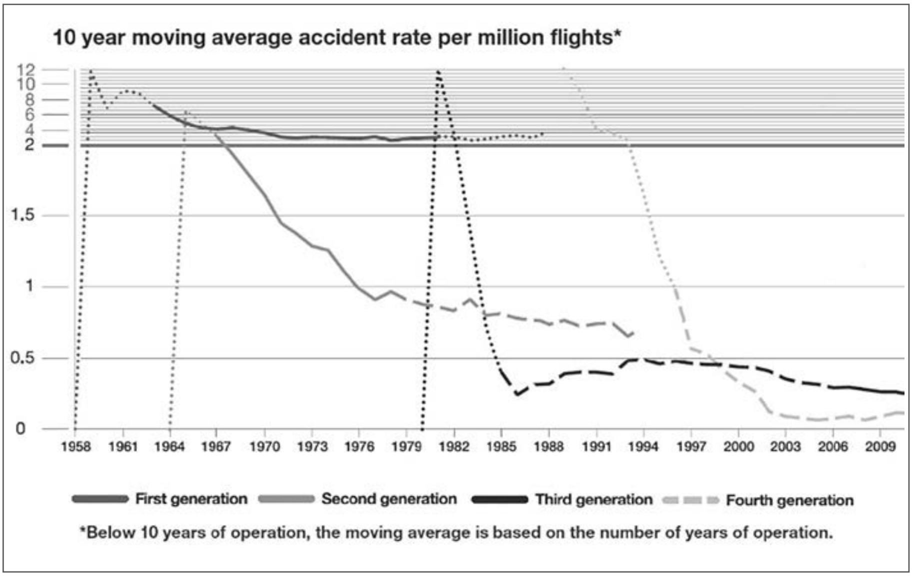


Figure 9: Rate of accidents during introduction of the four generations of Western design jets (Airbus).

References

1) *Air and Space Academy Dossier No.38, "Flying in 2050", 2013*
2) *Airbus, 2014, "Commercial Aviation Accidents 1958-2014, A Statistical Analysis"*
3) *Boeing 2013, "Statistical summary of commercial jet airplane accidents, Worldwide operations 1959/2013"*
4) *UK Civil Aviation Authority, 2013, "CAP 1036 Global fatal Accident 2002 to 2011"*
5) *UK Civil Aviation Authority, 2008, "CAP 776 Global fatal Accident 1997 to 2006"*
6) *UK Civil Aviation Authority, 1998, "CAP 681 Global fatal Accident 1980 to 1996"*
7) *IATA, Safety Report 2014*
8) *Mike Feary, NASA, "Evaluating Human-Autonomy teaming: How do we ensure Resilience?", presentation at the AAE conference of 1 June 2016: "Will air transport be fully automated by 2050?"*

2 SOME CONSIDERATIONS ON AUTOMATED SYSTEMS AND THEIR HISTORY

Author: Pierre CALVET

2.1 Initial remarks

Thanks to digital technology, commercial flights can now be almost fully automated: in an ideal, pre-programmed flight (still not totally feasible), the autopilot (AP) would remain permanently engaged, from take-off to runway clearance after landing. But to make the leap to a one or no-pilot crew?

Whatever progress can be envisaged for the future, whether through ongoing development or innovative breakthroughs, it will rely on data from the current situation and intentions inspired by observations of the past:

- *In the course of aeronautics history, progress has been driven by needs (wars or peacetime economic expansion) or innovative inventions (radiocommunications, servocontrol, digital technologies, satellites…).*
- *Reliant on a permanent association between humans and machines, aviation has never ceased to make steep demands of both: on the one hand, specialist training and excellent physical and mental qualities and, on the other, advanced technologies and great reliability.*
- *One remarkable aspect of aeronautics is the close interaction between designers and users, particularly during test and certification phases. A rigorous, prudently*

conservative framework means that even systems found to be satisfactory are perfected and enhanced over time.

- *In time, the accumulation of new devices, often similar or complementary to those already installed, has resulted in an overall lack of coherency. This situation is now being remedied by means of greater use of computers and ergonomic improvements to the human-machine interface.*
- *The growing number of cockpit instruments was justified by safety considerations: any dysfunction had to be detectable whenever possible and "compensated" by other substitute systems. Software solutions with varying degrees of transparency now improve pilot decisions, whilst at the same time simplifying instrument panels.*
- *The search for safety is a timeless constant, applied to a complex, global, rapidly evolving air transport system. Operational discipline results from a standardised set of rules and procedures, within a strict framework of organisations, infrastructures and verifications. Faced with increasing traffic density, operators, in particular flying personnel, must be given support to perform their tasks rigorously. This is a major goal of onboard automated systems and communications.*
- *The fact that accidents are ascribable to human action more often than equipment failure would argue in favour of increasing automation and communications to free operators from difficult, overly absorbing tasks. But pilots' experience and airmanship remain essential to safety in the many cases of unforeseeable danger that can only be dealt with to date by skilled humans.*
- *The flight crew of commercial aircraft was reduced from 5 to 2 members with the arrival of flight control automation, a cost-effective measure obtained without any compromise to safety. For the moment pilots have a higher decision responsibility than the systems they are in charge of. However, progress in artificial intelligence means that machines can now compete with humans in this respect: they are faster and tireless, although human intuition (so far) remains more powerful for non-deterministic behaviour.*
- *Whatever the automation level and demands in terms of communications, pilots have to supervise the proper functioning of these systems. This requires attention, as do the verbal confirmations or actions generally entrusted to the pilot not flying (PNF). Will this post one day be replaced by an "electronic PNF", or a kind of "prosthesis" for the captain/PF, who would thus be left solely in command?*
- *Finally, one might note that human physical and intellectual capacities are more or less constant due to their nature, while technological progress, which has been considerable in past decades, has no structural limitation. A short history of onboard automated systems reveals the qualitative leap they have instigated, in particular fly-by-wire controls and collision avoidance systems. Currently, developments in artificial intelligence are paving the way for more comprehensive automation, leading to increasingly autonomous flight control.*

2.2 Historical elements

Although flight can be programmed and managed automatically in recent airliners, unforeseen, dangerous situations frequently require action on the part of pilots. The human factor, though, remains a major causal factor in accidents: will safety be improved then by increasing automation and interconnections with the ground and with other aircraft? The constant improvement to the work of flight crews procured by technological developments in the past would seem to indicate so.

- *In the 1930s, there were four or five flight crew in the aircraft, initially assisted (physically) by servos then (more intellectually), by autopilots and VHF connections. Gyroscopes and radiogoniometers helped standardise IFR flights.*
- *After the Second World War, navigation benefited from hyperbolic positioning, then inertial measurement units, transistors and UHF (onboard transponders and radars). Dials and switches gradually invaded cockpits in successive layers until a newfound ergonomics enabled the departure of the radio operator and flight navigator. Pilot training changed as a result, regulations were oriented towards procedural flight control, supported by modernised ground control equipment (VOR-DME, ILS, secondary radars…).*
- *The development of jets from the 1960s on ushered in huge progress in avionics. The flight mechanic's instrument panel was replaced by "forward facing crew" cockpits and, with all instruments now within their gaze, pilots would gradually take over management of all systems. Two-member flight crews were generalised around 1980.*
- ***The advent of digital computers led to the introduction in the 1970s of fly-by-wire controls** capable of calculating aerodynamics equations. With propulsion automated, **almost all functions of flight control could be integrated, first into the autopilot and the FMS and then into automatic landing, flight envelope protection and collision avoidance systems** and the correction of various anomalies.*
- *Nowadays, automated systems leave pilots with little more than a thorough monitoring role: **programmable "glass cockpit" screens and reconfigurable displays, including GPS and weather radars**, offer a relatively precise panorama of the situation at all times. But automation can sometimes complicate detection and understanding of incidents; the unexpected compels humans to use their intuition, which works on a higher level than the logic of current robots, to counter the risk of a "**cliff effect**".*
- *In this case, despite the spectacular success of drones and artificial intelligence, can we really conceive of eliminating the onboard pilot? Or rather should we **reinforce co-operation between pilots and automated systems** to avoid incompatibility and inappropriate operations in extreme circumstances or during degraded flight? **In the end, machines should be provided with a higher "intel-***

ligence" enabling them to become one with humans, and joint efforts on the part of engineers and cognitive engineers should provide these operators with the corresponding "mental prostheses".

2.3 Current characteristics of onboard automation

Formerly installed as individual pieces of equipment, nowadays as a subset of a multifunctional system, each automated system can be characterised by its passive or active function:

- *a **passive** instrument presents information on a dial or a screen (for example, the attitude indicator, now integrated into the PFD). The evolution towards multi-media is tending to confer on this information a prompting function, inciting appropriate actions from the operator, such as to alter system settings if required or as orientation to fly the aircraft;*
- *an **active** system replaces the operator by ordering or driving controls, the most obvious example being the AP. A large variety of active automated systems exist on board, from the simple servo to the FMS, which programmes all flight control operations.*

*Since each piece of equipment relies on sensors (Pitot, gyroscope, accelerometer…), two redundant instruments must not, for safety reasons, depend on the same sensor. The arrival of digital computers radically transformed the systems architecture; **software** offered more flexibility and resilience by means of:*

- *varying degrees of automation for reconfiguration of subsets (sensors + passive indicators + active controls);*
- *automatic switches to identify and isolate a defective element;*
- *ensuring the safety of subsets, including self-repairing subsets;*
- *function sequencing and **integration** of equipment into a centralised system… (multimode AP controls, programming by the FMS…).*

Due to the complexity of current automated systems, special attention is required during their activation, deactivation and any mode changes. Continuity in control surface position and engine speed must be ensured during these transitions, which must not affect the situation inside the flight envelope.

Steps were taken recently to failsafe these delicate phases and prevent inappropriate operations, particularly in the event of system component failure or degraded flying conditions.

Collision avoidance between aircraft or with moving ground obstacles has been provided in past decades by airborne radars and specialised transponder (TCAS), which require compatibility between all the equipment involved. An extension of *these inter-connected systems is being developed in projects for new air-to-air and air-to-ground communication networks, ATC-linked or not.*

2.4 Summary and perspectives

Transformed by the greater availability and sophistication of microcomputers, avionics now play a leading role in flight control. Changes to computer systems architectures that are underway or in the pipeline include digital multiplexing, local area networks (LAN), optoelectronics, massively parallel computing, and new neuronal techniques now available to cognitive engineers.

As a result, the role of humans in the "aircraft system" has evolved. Regarded as "super-robots", they act at a higher level of intelligence and intuition than machines, for the moment at least, although the form of intelligence known as "artificial" is rapidly closing in on our own.

The art of flying an airliner has thus moved gradually but fundamentally away from basic initial training. Training in airmanship retains its specificity and still reflects the vocational aspect of the pilot's profession, but the skills required are very different to those of the airline pioneers. Current aircraft are dominated by computer systems and flying them requires less manoeuvring skill but a keener intellectual understanding than before.

Design is therefore likely to be reoriented with a view to:

- *on the one hand, harmonising and integrating the actions of new pilots to more and more highly automated aircraft functions;*
- *on the other, restricting human intervention, although necessary, to the increasingly rare occurrences of unexpected and dangerous situations.*

When the accident probability is low enough, it will be time to entertain the idea of doing away with the onboard pilot.

These remarks are based on the observation that historical changes have gradually given automated systems and communications greater and greater responsibilities in flying the aircraft, gradually transforming the activity of the flying crew. Less and less bound to their joystick, pilots are nonetheless irreplaceable when dealing with the myriad of unfortunate surprises and incidents encountered during each flight, which could otherwise degenerate into catastrophes.

Another interpretation of history, in reverse, might take missiles and the space adventure as a starting point for automation. Unmanned missiles were initially launched at a predetermined target, before being granted some flexibility to include moving targets and necessary changes of trajectory in the course of flight. And now, drones…

Instead of increasing automation in two-pilot aircraft, with a view to eliminating one of the pilots, would it not be possible to enhance drones and make them more *secure by introducing a minimal human presence on board? In other words, go from no pilot to one pilot according to the needs of an unmanned drone, instead of applying the opposite approach to traditional aircraft? This suggestion is clearly limited to a research rather than pre-development stage, since very few drones exist on which this could be tested.*

3 BASIC THEORY OF AUTOMATIC FLIGHT CONTROL

Author: Jean-Claude RIPOLL

Automation in passenger air transport; a theoretical and philosophical approach to flight control

3.1 Summary

The aim of this chapter is to develop a methodical approach to flight control automation – from initial alignment to runway clearance – and to compare the existing situation with this new approach. The notion of piloting is taken as representing the highest level of tactical and strategic decisions governing actions applied to the aircraft's flight control surfaces. In this approach, the different piloting modes are identified and sorted into a hierarchy, resulting in a strict architecture for automation. The human/machine relationship within the flight control loop is analysed and the concept of crew extended to include all players, including automated systems and the ground. In the very long term, the fully automated aircraft will be a robot, capable of carrying out the recurring tasks of an entire mission. It will nonetheless remain under the control of an onboard human operator, who will manage un-programmed (unforeseen) situations with the help of appropriate controls. Automated systems contribute to safety and crisis management. This configuration, which it is hoped may materialise within several decades, will be the result of a "cybernetic transition". A vast development programme should be launched, including demonstrators for automated systems, in order to achieve this robot.

3.2 Introduction

The notion of flight control automation, initially limited to the execution of tedious tasks, has evolved to encompass facilities making it possible to reduce the onboard crew to two persons, even in the face of greater complexity due to air traffic growth, a multiplication of air routes and growing airport congestion. For the system to evolve coherently, automation will have to be extended to all areas of air transport, leading to a cybernetic transition. The ambitious "theory" sought in this chapter is in fact the search for a logic in the piecemeal implementation of flight control automation. This logic can be found in a physical analysis of flight control which classifies the various automated systems, current or future, in order to articulate them in an optimal way, particularly from a safety standpoint. It would however be interesting to compare concrete examples of use with the approach concepts attempted here.

3.2.1 Principles

There is always a pilot… at the heart of a crew. The full aircraft crew already comprises one or more persons on the ground, permanent or temporary, a feature that will only continue to develop. Automated systems also form an integral part of the crew. As a result, human-machine interfaces fall within CRM (Crew [or Cockpit] Resources Management) and CDM (Cooperative Decision Making) management procedures.

Whatever its level of automation, no aircraft, manned or not, is ever (normally) left without a supervisor or "ultimate controller" to monitor its functioning and modify the mission.

There will always be a human on board, representing the entities responsible for authorisation, organisation and operation of the transportation service; authorised to intervene in flight control, this person shares the fate of the passengers. For as long as the pilot is available, they are the ultimate supervisor.

There will always be cases where an automated function will become unable to continue the task in progress, and will need to be replaced by a human operator. Provisions must be made to ensure that this takeover is as easy and effective as possible. This stipulation leads to the concept of a "default" automated mode, ensuring a minimalist flight configuration. A situation in which the onboard operator was incapacitated would call for ground assistance.

3.2.2 Definitions

"Automated systems" carry out programmes according to set parameters; "robots" take external information into account to adjust the programme to be carried out. ***Simultaneous operation of several automated systems, with joint interfaces, does not constitute a robot.***

A robot is capable of dealing with the ***unexpected*** *(a situation identified as possible but not anticipated for the flight in progress, as determined by the built-in programme), but cannot deal properly with the unforeseen, which by definition has not been programmed or even identified as possible (within a certain degree of probability).*

3.3 Flight control and management

3.3.1 Dynamics

*The **first stage** of flight is the creation of those forces required for acceleration, in accordance with the principles of dynamics. The **second stage** is the integration (in the mathematical sense) of acceleration, modifying the speed vector. The **third stage** is the integration of speeds – movement – which produces a trajectory (in the kinematic sense). Because of the origin of these forces, the trajectory is defined in the "air" reference frame. The **fourth stage** is the assemblage of successive trajectories, which leads to a well-defined ("4D") spatiotemporal point, positioned either in the "air" reference frame or in the "ground" reference frame. This assemblage is qualified here as a "manoeuvre". The **fifth stage** is naturally the assemblage of manoeuvres by which the goal of the flight is achieved; this full itinerary is qualified here as "mission".*

3.3.2 Flight control modes

*Five control modes, or levels, are attributed to the five stages of flight operation. At flight level "**5**", flight control automation consists of assigning an onboard "**robot**" (classified as "**substitute**") with the task of developing and executing a flight plan, respecting all appropriate rules. During flight, each time the flight plan is called into question by external information obtained by the robot, or at the request of the onboard operator, or because of an anomaly on board, the robot will propose several solutions to be chosen by the operator. Once the manoeuvre to be carried out (level "4") has been defined, it is translated into a series of trajectories by a "**delegate robot**", on condition that the substitute robot has defined a safe, legitimate operation (prohibited zones). These trajectories, which will be monitored in the "air" reference frame, are organised so as to lead to the spatiotemporal point of end of operation. The delegate robot commands the execution of these trajectories, in the form of a hodograph (speed vector described according to time by its module and its three-dimensional orientation), by "**automated systems**" (level "3"), which define movements and accelerations (level "2") obtained by adjusting or moving (level "1") the control surfaces.*

The conventional pilot is responsible for all the modes described above. According to the degree of automation of the aircraft, the pilot/operator can choose the mode to be implemented: handling controls on levels 1 and 2 ("pilot"), setting parameters for automated systems on level 3 or managing the robots of levels 4 and 5 ("operator").

3.3.3 Hierarchy of flight control modes

Mode 1 automation does not come under the terms of study here. Servos increase the pilot's power. The latter is in charge of determining the commands to be followed, according to information received.

Mode 2 is not automated while in normal flight, but does allow for the inclusion of automated functions (qualified below as "intruders") to protect against abnormal or excessive commands on the part of the human pilot. Such commands will not be given by automated functions of a higher order. The pilot's commands are translated into action by computers on the basis of control laws that enhance the pilot's handling skills. These two modes are based on an economy of means. The following modes proceed from an economy of results, with the pilot/operator demanding a specific flight control result.

Mode 3 is an "autopilot" mode. Current automated systems do not always respect the concept of control by hodograph; this deficiency must be corrected. Open loop functioning necessitates constant monitoring.

3.3.4 Levels of robotisation

*Modes 4 and 5 are **levels of robotisation**:*

- *the "delegate robot" receives detailed instructions for carrying out its task, and assimilates further information whilst performing the manoeuvre. The distinction is not always made for automation currently in place between an automated system and a robot, a confusion that must be cleared up;*
- *the "substitute robot" is given specific results to be obtained, but itself gathers the external and internal information needed for scheduling manoeuvres, translating this scheduling into instructions transmitted to the delegate robots.*

The scheduling worked out by the substitute robot (or rather by the algorithms with which it is programmed) is submitted to the onboard "supervising operator", unless the latter becomes unavailable, in which case a special procedure must be implemented.

The closed loop mode of these robots requires less close monitoring, particularly in certain phases and environments. The substitute robot could be said to raise the prospect of pilotless flight, but in fact leads rather to a revision of criteria governing flight crew composition and activity.

A fundamental conclusion of the analysis carried out is the hierarchical structure of the set of flight control modes, and consequently of the automatic flight control system as a whole.

The operator in charge of the flight must provide the automated systems with all the information they require to perform their tasks, and the automated systems must not be capable of functioning if this information is not complete and coherent. In this way, a hierarchical system is built up in which humans have primacy.

Each automated system must have access to all lower ranked systems necessary to its functioning, and must at the same time provide the latter with all data characterising their tasks. The position of each proposed automated function in the overall system must therefore be clearly identified along with its links to other automated functions. The confusion between automated system and robot is a dangerous one; certain devices can apparently be seen as being robots (enjoying a certain autonomy) whereas in fact they are only automated systems (requiring monitoring).

3.4 Design and implementation rules

The preceding analysis leads to a definition of rules for the design, implementation and use of automated functions in the flight control system:

***Rule 1**: Precisely identify the place of each automated piece of equipment in the overall system and its function in the corresponding flight control mode (clearly distinguish between robot and automated system, and between automated system and flight control computer).*

***Rule 2**: Strictly respect the hierarchical structure of the system: each rank N automated system should receive commands only from the N+1 level, and give them only to the N-1 level.*

***Rule 3**: Ensure that each automated system is fully complete and, if not, downgrade it to the rank below, as follows:*

- *a rank N automated system must be able to command all rank N-1 automated functions necessary to its operation;*
- *a rank N automated system must take into account all the data and information determining the execution of its function.*

***Rule 4**: In the case of loss of function of the N mode selected, the system must return to the N-1 mode, and not to N-2.*

Complementary rule: in such a situation, the N-1 mode must maintain safe flight until intervention by a (human) operator[5]. Return to N mode must be controlled by this operator.

***Rule 5**: No automated system must be able to start functioning if the information and commands it has received are not complete and coherent.*

Complementary rule: the validity of commands and information must be obtained in a minimalist form.

***Automation of the onboard system**: Automation can be sorted into four categories:*

	Flight control	Support
Active	*COMMANDERS*	*INTRUDERS*
Passive	*ENHANCERS*	*INFORMERS*

Table 3: Categories of automation.

Flight control is managed by the automated systems and robots whose commands are carried out by flight control computers and control service servos. Other automated systems again must be set in place to ensure safe, effective flight control. "Informers" provide parameter measurements as to the physical state of all components of the aircraft and the aerodynamic and environmental situation as well

5 *This rule requires the rank N-1 automated system to indeed be in a position to control flight, i.e. to have access to all information necessary and to all automated systems of the rank below. Therefore: the coherence and comprehensiveness of data must be checked automatically on the basis of appropriate models.*

as data on weather, circulation and traffic conditions, received from external data bases. This information is processed to be presented to the operator/pilot, formatted for use by the automated systems and/or interpreted to provide useful alarms or messages to the operator and/or the ground. "Intruders" react against a dangerous order (overstepping of limits, impact trajectory) and can even impose a hodograph (go-around). Interactions between these automated systems must not create incomprehensible chaos for the operator. Hence the complementary rule:

***Rule 4 b**: Intrusions or prohibitions should not have the effect of returning to a flight control mode lower than level 3 (hodograph). Excepting, obviously, prior adoption of mode 2 or 1.*

3.5 Dealing with the unexpected and the unforeseen

3.5.1 General considerations

Automated systems are programmed to react to situations that have been identified and taken into consideration by designers, but which are unexpected within the framework of the flight plan in progress. Modes 4 and 5 do not give proscribed commands. Intruders can interrupt a dangerous or illegitimate mode 3 trajectory. A common mode is the loss of information needed for flight control; this situation must be pre-empted by reliable, fully redundant measurements (both technology and placing of sensors). The introduction of a digital model of the aircraft is considered to provide acceptable "recovery" values for flight control by means of coherence and continuity calculation. Situations that have not been anticipated (for various reasons) are by definition unforeseen, and cannot be dealt with by automated systems: the principle adopted here is to transfer control to the human pilot/operator. This resumption of control should make no extraordinary demands of the human operator, whether physically or intellectually. Automated systems must provide the human operator, the only one capable of resolving the situation, with an integrated overview, enabling them to perform integrated trajectory control. Information presented should be directed at the "solution", not the "problem", i.e. should highlight available resources. Technical progress, including the globalisation of interconnected broadband networks with immense data-processing resources, will lead to onboard or ground solutions.

These considerations encouraged us to envisage a default flight control programme for level 3, based on elements as reliable as flight control systems, whether engaged automatically or manually, which leave humans time to react.

3.5.2 Two special cases

Even before widespread adoption of modes 4 and 5, it is possible for to plan for a re-routing controlled from the ground in an emergency procedure when dealing with an extreme situation (total incapacitation on board, hijacking). Conditions for implementation are not those of automation as such.

In the final phases, it is in fact air traffic control that flies the aircraft, by ordering either relative manoeuves between aircraft, or trajectories (heading and speed), i.e. piloting in the air reference frame to carry out "ground" operations. ATC controls a group of aircraft with varying configurations: interactions between the automated systems of the various aircraft must not lead to chaos. Algorithms must be adapted to the different flight phases. ATC will need to be capable of ordering automatically generated manoeuvres, digitally transmitted directly to flight control robots.

3.5.3 Role of modelling

Modelling is omnipresent, from design to certification. Onboard computing capabilities ("real time embedded software and systems") make it possible to base automation on modelling. The robot, based on a generic model of the type of aircraft and mission, receives instructions for performing the flight that are in line with traffic rules, and integrates them to produce the flight plan. This robot calls on a model based on the specific aircraft (model, aerothermodynamic characteristics, loading, state of consumption, etc.) which provides it with the parameter values necessary to produce appropriate commands that are then given to the automated systems carrying out the trajectories. Generic algorithms deal with aims and results, whereas specific ones deal with means. The algorithms of generic robots are thus shared by a broad population, thereby facilitating ATC management and paving the way to remote control without in-depth specialisation of the operator.

3.6 Human and automation

3.6.1 Process loop

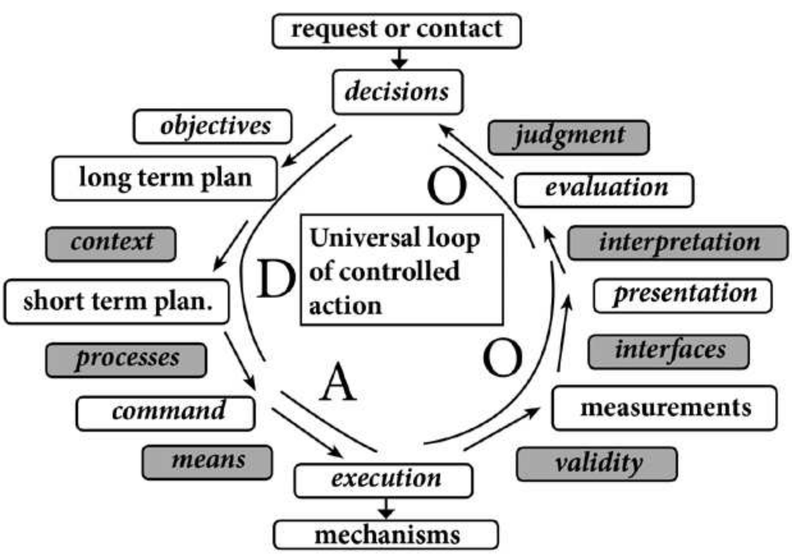


Figure 10 : Process loop.

Not only do we consider the presence of an operator/human pilot on principle, but it is clear that automation will only be partial for some time to come; it is consequently necessary to analyse flight control with a "human in the loop". Any form of "system" control calls on a universal, fractal loop, for which the prototype is the OODA loop (Observe, Orient, Decide and Act, see Figure 10, p.94). By extending this loop to flight control, light is thrown on the task-share between automated systems and humans according to the control mode adopted. It should be noted that the following are always automatic:

- *execution of commands by the computers and control servos (engines included);*
- *gathering of measurements by onboard sensors;*
- *processing of measurements and how they are displayed.*

In modes 1 and 2, the human/machine interfaces are thus at the boundaries of these installed systems: the presentation of measurements must cover all terms of flight control.

On level 3, the interface moves from execution to command: the pilot/operator must have a clear, integrated interface defining the hodograph in four dimensions in a simple, reliable way; likewise the presentation of measurements must be clear and coherent with the order.

At level 4, the two interfaces move to relate to hodograph scheduling and situation assessment. On level 5, the control interface moves to planning. Each time, the interfaces must be adapted and must focus on those functions devolved to humans, with robots capable of managing the rest of the loop. The flight display must identify, both instantly and unequivocally, the mode currently in service. On levels 4 and 5, the robot manages the entire loop as long as there is no assessment anomaly. In fine, when the robot is defective, the human intervenes and, after judging the assessment, decides on the new goals to be reached and launches a new planning. At this level, the robot is managing an autonomous loop and the human is "above the loop", employing his/her high-level faculties.

3.6.2 Automation and safety

Each process representing the achievement of a stage in the functioning of the loop relies on a flow of information and is subject to disruption and dysfunction, if not failure. Automatic devices can be set up to identify, highlight and even correct these dysfunctions. The material condition of the entire aircraft is already monitored using ground reports (OCC, maintenance) and sometimes by means of auto-repair. The power of automation is more preventive than curative, the priority should be to develop this preventive action. All stages of human intervention can be monitored (for coherence and comprehensiveness) and even corrected by automated systems. Automated systems can (and must) intervene on four levels: monitoring, protection, safeguard, rescue. Compliance with the above mentioned hierarchical structure and rules is essential to prevent these automated monitoring systems from creating problems for the operator/human pilot.

In addition, the possibility of ground assistance and even resumption of control has been evoked within a context of security risk. It is not automation itself that is in question but rather how it is employed, in particular to enhance the manpower and qualification of onboard crews, a utilisation that raises some tricky issues (availability, integrity, security of telecommunications and players).

3.7 Future prospects

3.7.1 For the air transport system

Automation will gradually be extended to encompass all areas of air transport, leading to a cybernetic transition that includes all operations carried out by the different ground players within the sociotechnical context of the time ("Big Data", the "cloud", the "IoT, Internet of things", permanently connected objects and populations). These permanent, universal networks connecting players and objects will ensure the necessary availability of up-to-date, reliable information. There will be no ATC "big-bang". The rules of the air will be the same at all times and for all aircraft. The progressive integration of drones into civil traffic requires a single set of rules. Aircraft will evolve in virtual airspace (dematerialised definition), segmented by digitally defined partitions, delimiting zones that are open dynamically to the various types of operation. Future equipment will make it possible to at least partially delegate separation management to aircraft. The role of OCCs will not change fundamentally but could increase in the area of assistance to onboard crew.

3.7.2 For aircraft

Direct action on the servos has almost been, and soon will be completely abandoned. Manoeuvre control has become commonplace and is the current basic fallback mode. Given the available technological level (reliability and mastery of flight dynamics), it is the "hodograph" mode (local trajectory) which must become the rule for flight control at the minimal automation level of "resumption of control". Hence the recommendation to develop and implement an ergonomic device for local trajectory management (hodograph), comprising display and control. Traditional controls then become unnecessary.

This disappearance of traditional controls is a remote prospect. For the moment it will be necessary to accept the return to mode 2, or even 1, on conscious decision of an authorised operator. Aircraft handling will thus be performed first with traditional controls, then with miniaturised emergency controls (as for model aircraft). The future should see the level 5 "mission" mode prevailing in a system where automation will encompass all players (ground included) in a coherent way. The next step, preceding this stage, should be to place at the crew's disposal a full, coherent set of "delegate robots" allowing full flight control by manoeuvres.

3.7.3 Conclusion

The purpose of automation cannot be to eliminate the human operator. In-depth study shows that humans and machines are irreducible. Consequently human and machine must work together as a team – onboard. The complete crew actually already includes one or more parties on the ground, a tendency that will only increase. It will eventually become technically possible for a complete transport mission (a "meta-mission") to be performed by robot substitutes sufficiently autonomous to ensure the return trip even in the event of re-routing (some military prototypes are already capable of this). But this will not lead to the human operator being eliminated. Rather it will call for a redefinition of the functions and competences of each and an ensuing adaptation of the instrument panel and the processes of selection and training. Without necessarily needing in-depth knowledge of the "physiology" of the entire automated system, operators will require full, conscious command over its behavioural logic.

The strict hierarchical structuring of the system will see the mixed human/machine loop (with the operational complexity outlined above) giving way to a hierarchy of "loops" of increasing intelligence levels, in which the human loop is reserved for judgement and decision functions of which the machine is incapable (decision-making being outside the realm of programming). These technical possibilities will impact crew management.

3.8 Proposals

The framework presented here will have to be supplemented by an analysis of societal, regulatory, certification and (international) legal issues, not to mention the economic component.

Automation is not fundamentally curative, on the other hand it can be preventive. It is advisable therefore to put maximum emphasise on prevention to cut to a minimum the likelihood of cases of powerlessness. This approach could be a permanent guide.

It would be wise to first build a more reliable, minimal system, that provides backup in critical situations. The cockpit must be redesigned, eliminating the dual workstation and traditional controls in the long term.

Given the momentum of the system, the substitute robots controlling the automatic aircraft (equivalent to an autonomous drone) will initially be installed on more traditional (next generation) aircraft and put to the test of the dual control system. Operators will have the choice between the "traditional" and "robotised" modes.

These "mixed" aircraft will pave the way for the transition: maintenance of a minimal "manual" piloting skill for as long as necessary, training in flight control by way of robots (delegates then substitutes), development and qualification (certification) of *said robots after a "learning" process under the control of experienced human operators.*

***It would be advisable to launch an ambitious, long-term European development programme comprising demonstrators, on the theme of flight control automation**, ensuring:*

- *the universality of solutions demonstrated;*
- *their acceptability and industrial implementation on a world level;*
- *the progressive implementation of the system by means of consistent, standardised levels.*

In its pre-competitive stage, this drive towards automation should benefit from broad international co-operation, so as to arrive at identical concepts and common requirements.

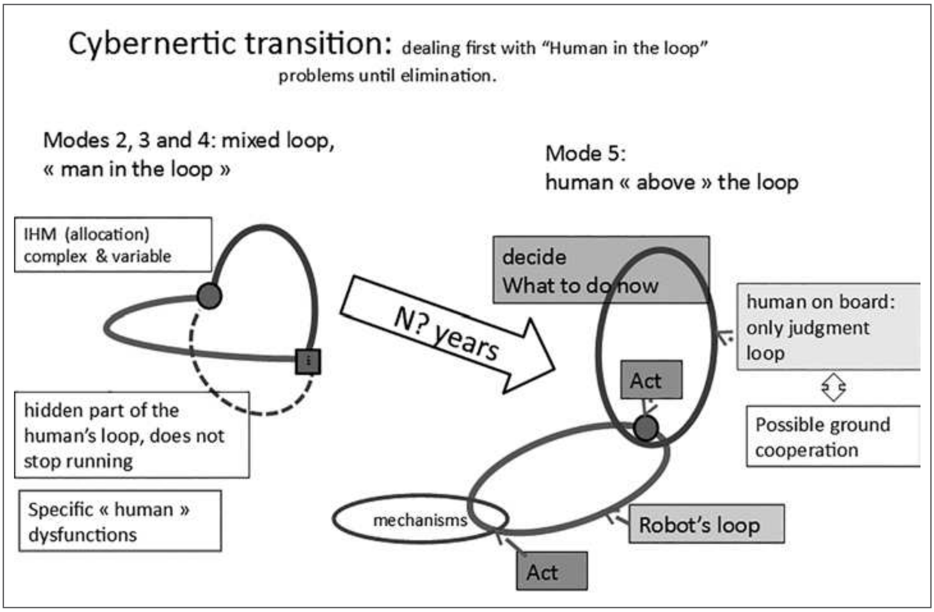


Figure 11: Towards more cybernetics.

4 ARE PILOTS NECESSARY ON BOARD?

Author: Jean PINET

4.1 The current situation

4.1.1 Basis for the analysis

Answering this question means analysing the simultaneous development of two "super-agents" working in symbiosis, although virtually independent.

4.1.2 The Human super-agent: the flight crew

In operational situations, the behaviour of human super-agents strongly resembles that of the automated systems they themselves design and use. Here are some key features of this human automation:

- *It has certain operational limits:*
  - conscious actions are processed in a sequential way;
  - each conscious elementary action is stored sequentially and chronologically in the short-term memory (which has a limited capacity of between 10 seconds and 2 minutes);
  - in unexpected situations, attention focus can lead to short-term memory saturation;
  - a prolonged absence of salient information can, on the contrary, lead to loss of vigilance.

- *Time is essential to its functioning:*
  - every mental action has a duration;
  - the time available for a task determines how it is performed.
- *The quality and relevance of sensory information, particularly visual, determines the validity of perceptions, potentially reducing reaction time and simplifying mental tasks, It therefore shapes choices and actions.*
- *Accurate processing of perceptions relies on:*
  - the quality of the mental models transforming knowledge into memory;
  - the experience and knowledge gained through training;
  - the self-control and know-how gained through appropriate selection and training;
  - the salience of information;
  - physiological factors such as fatigue.

Despite individual differences, commercial aviation pilots worldwide share many operational characteristics.

4.1.3 The automation/prosthetics super-agent

Automated systems can be viewed as prostheses placed at pilots' disposal to help them with aircraft handling and mission management. This notion of mental aid is an accepted one in robotics.

They are designed to function on two levels:

- *low-level intelligence: this first, deterministic level is used in current equipment;*
- *high-level intelligence: this second level is designed to replace the non-deterministic functions of the intelligent human automation system. Such functions require adaptability, operational efficiency, reliability and validation, making them very difficult to develop and certify at present.*

To be viable, these prostheses must take human operational limitations into account. Today prostheses/automated systems have invaded the cockpit after an opportunistic introduction of new functions, layer by layer, as technology advanced.

Mental prostheses can still be greatly enhanced as long as two principles are respected: appropriate arbitration between the mutual capabilities of humans and automated systems, with the latter being adapted to take account of human limitations. Such improvements are anyway needed in the interface for two-pilot crews, for example flying defined-objective aircraft trajectories.

Although humans remain unchangeable, they can be adapted to their mission as long as fundamental limitations and capabilities are respected. 30 years ago, for instance, it was an error to rely almost completely on automated systems in training, to the detriment of basic airmanship, which enables an aviator to control dynamic movement in a three-dimensional space.

4.1.4 Characteristics observed in the Human (crew) super-agent

Human reliability is essential to carrying out a mission; the following aspects should therefore be considered:

- *Failures in operational reliability leading to accidents (easy to quantify because infrequent) are usually linked to an overstepping of the human limitations listed above, often due to an inadequate pilot/aircraft interface (ill-adapted to unexpected situations for example).*
- *The multitude of actions taken by pilots in normal flight to avoid dangerous deviations after unexpected situations, on the other hand, are a vital, often overlooked aspect; despite being around 5 million times more frequent than failures leading to accidents, no quantitative research exists on them. This should be remedied to highlight the positive impact of human presence in countering commonplace deficiencies.*
- *Due to the physiological fallibility of humans, their presence must be duplicated.*
- *Two-pilot crews have certain notable weaknesses in terms of reliability, but mutual assistance remains very constructive although, once again, no quantification has been made of these positive aspects. No figures have ever been established as to the impact of two-pilot crews in reducing the accident rate.*
- *In terms of psychological reliability, the difficulty of detecting any tendency to dangerous personal initiatives is highly problematic. A huge effort must be made to improve pilot selection and monitoring. The experience of the military should serve as an example.*
- *Motivation and ethics play an important role in personal reliability, but remain within the uncertain realm of the individual.*
- *The remarkable operational resilience of pilots in the great majority of tasks entrusted to them is undeniable.*
- *Lastly, it is worth noting that the principle of dissimilar redundancy adopted for avionics applies to both the human-automation coupling and two-pilot crews.*

4.2 The future

4.2.1 Reducing the number of pilots on board

The decision on whether or not to reduce the number of pilots on board is based mainly on:

- *financial considerations (cost of crews, in training and in operation, recruitment difficulties);*
- *unstoppable progress in technology.*

The choice is presented in a loaded way based on a quantification of costs together with an analysis of the percentage of human failures in accident causes. But since, *as mentioned above, no figures are available concerning the numerous actions taken by the crew that contribute to safe, efficient missions, there can be said to be a lack of logic (bias?) in the official demonstration.*

In order to introduce more logic into reflections on the possibility of reducing the crew, a brief qualitative analysis is performed below, in which the human "automation" is replaced by autonomous systems in the trickiest cases, i.e. unexpected or unforeseen situations, with or without initial loss of vigilance.

These autonomous systems present:

- *positive aspects:*
  - capacity to collect many quantifiable parameters on the state of the aircraft and the environment;
  - capacity for memorisation;
  - no need for sequential processing of many physical parameters;
  - no need for short-term memory capacity, no attention tunnelling;
  - rigorous, rapid processing;
- *negative aspects:*
  - difficulty to define the necessary set of sensors, their compulsory characteristics and properties and the requisite combinations/hybridations of sensors/signals;
  - difficulty to detect and sort out the relevant elements for characterising a critical situation and taking corrective action;
  - difficulty to define all necessary memorised algorithms, adapt them to the environment and validate them;
  - difficulty to make critical choices, particularly in complex and/or unexpected situations.

To fully understand and design an autonomous system, it is first necessary to define the functions that will replace or do away with the human functions of attention, conscious and subconscious awareness, situation awareness, sequential processing and its saturation.

Moreover, data acquisition and learning functions must be defined even for low-level intelligence.

To conclude, a large number of clearly defined situations could be dealt with autonomously, but complex situations involving difficult choices will remain the realm of human beings for some time to come. Air transport missions form a relatively well-known group today, but how is it possible to automate the flexibility required by the great diversity of environments and situations, as well as the need to adapt to unforeseen and unexpected events?

Wherever they are, humans responsible for flight handling will rely on accurate, immediate knowledge of any critical onboard situation for a very long time to come.

4.2.2 A single pilot on board

By analysing the current tasks and functions assigned to the PF (Pilot Flying) and PNF (Pilot Not Flying - we consider the term of Pilot Monitoring to be inappropriate), one can define whether to allocate roles:

- *to automated systems, i.e. whatever they do better than humans;*
- *or to the single pilot (SP), i.e. those tasks requiring choices and decisions beyond the capacity of automated systems (qualitative and ethical choices and unforeseen, even unexpected situations).*

However, the single pilot must be assisted in certain circumstances:

- *total or temporary incapacitation;*
- *situations involving a heavy workload;*
- *dangerous, rapidly evolving situations;*
- *monitoring;*
- *loss of vigilance, drowsiness;*
- *dangerous individual/terrorist act.*

An analysis of assistance possibilities leads to the following conclusions:

- *Onboard assistance by any person other than a pilot with direct responsibility is impossible in rapidly evolving, dangerous situations.*
- *Assistance by ground staff remains problematic and conditional; it cannot meet the needs of rapidly evolving, dangerous situations.*
- *The nature of such assistance varies according to circumstance, flight phase, urgency and aircraft type. Personnel assigned to such functions can be generalists if the situation in question allows for this and sufficient time is available. They can simultaneously assist several aircraft if none of these is in a time stressed situation or has specific technical demands. Emergency situations require permanent assistance and most call for at least a copilot's level of knowledge of the aircraft. So no general standard can be defined for application to all personnel.*
- *Situations involving pilot incapacitation or dangerous individual or terrorist action require protective measures that are independent of the onboard or remote pilot's authority and which differ according to flight phase and environment. Cybercrime also remains a cause for concern.*
- *Recent regulations requiring the permanent presence of two persons in the cockpit risk considerably affecting opinions as to SP operations.*
- *One challenge not yet resolved is how to train single pilots to directly assume the post of captain when regulations insist on their acquiring a minimum level of experience before being able to assume this post. Ground training on FFS (Full Flight Simulator), for instance, is far from providing the quality needed to deal with critical situations.*
- *Selection, training and skills maintenance of assistance personnel, whether onboard or on the ground, should be meticulously studied, defined and costed.*

- *Air-ground transmission raises issues of quality, volume, transit time, latency, continuity and reliability (in the event of solar eruptions for instance). It is of vital importance in emergency situations and must be protected against any malicious action.*

To assist the SP, complex operational systems must be set up involving ATC and airlines. These demand an increase in the immediate autonomy of the aircraft and the progressive introduction of non-deterministic functions in aircraft systems (high level of artificial intelligence) and therefore a carefully validated learning capacity.

This can only be achieved step by step, integrating elements in a complex manner as they become available, through limited experimentation and an obligatory in-flight section for correct validation. A probabilistic use of risk assessment will be the key to progressive decisions. For example, SPs could begin their experience in situations with reduced statistical risk, such as short- and medium-haul flights, or during cruise phases of long-haul flights.

Each stakeholder's investment will depend on their judgment of the market and the costs involved, but comprehensive studies will probably be commissioned and funded as usual by state organisations and major industrial groups, at the cutting edge of innovation.

Rules and methods will have to be defined to validate technologies and certification procedures, a tricky task for certification authorities.

4.2.3 In brief

In 2050 and even beyond, there will still be at least one pilot on board.

To recapitulate, the evolution towards greater autonomy in flight is irresistible, but will only be possible on condition that we:

- *leave pilots do whatever they can do better than automation, particularly in unexpected or unforeseen situations;*
- *take human capacities and limitations into account in any pilot-aircraft combination, to ensure successful integration with the automated systems-prostheses designed to increase the effectiveness of the duo;*
- *provide pilots permanently, wherever they may be, with an accurate perception of any situation, which means reviewing the nature of the information they receive as well as the means to send it.*
- *avoid any "cliff effect" in emergency failure situations;*
- *do not cancel protections in degraded flight modes or after involuntary departure from the normal flight envelope;*
- *select and train pilots in self-control, risk assessment, basic airmanship, recovery after flying outside the flight envelope;*
- *solve the problem of vigilance.*

Full autonomy, with no onboard pilot, cannot be envisaged by 2050.

It is not desirable from a safety point of view.

But partial autonomy, in certain identified cases and conditions, will be possible, and will be progressively installed.

Interactions and connections between systems responsible for autonomy will require more and more complex software to process, verify and monitor the combinations of possible cases. The risk of unforeseeable knock-on effects will rise.

***The decision to reduce the crew to a single onboard pilot is unrealistic if based on economic grounds alone**, given the associated technological, safety, financial (always underestimated) and societal issues.*

The choice of autonomy solutions and the question of reducing the number of pilots on board should be dictated by risk assessment and induced costs. Such an assessment, based on probabilistic statistics, is not possible today, since present studies do not counterbalance known rates of human deficiency by the positive impact of situations resolved by pilots, which are millions of times more frequent. A quantified assessment is needed in order to gauge the potential benefits as compared with the current situation. Far-reaching statistical research should be carried out.

The sheer number and variety of issues at stake in such a decision point to the need for a global, statistical study of risk management, both accurate and detailed, including all stakeholders: airlines, manufacturers, ATM, training centres, certification authorities.

SPs will not be able to deal with all dangerous situations, but neither will automated systems nor external/internal assistance. The current regulation compelling airlines to have two persons permanently in the cockpit should be carefully considered, since it can either simplify or complicate matters according to the professional status of the associated person. These choices require careful arbitration which only certification authorities will have the power to do.

The complexity of the software and probabilistic calculations involved will probably compel such bodies to find new methods of certification.

On the other hand, important progress can be made to two-pilot flight handling.

5 ANALYTICAL APPROACH TO EVOLUTIONS IN FLIGHT CONTROL WITHIN A 2050 TIMELINE

Author: Jean BROQUET

5.1 Towards safer, more cost-effective flight control

Human flight control errors are currently the primary cause of almost 50 % of fatal accidents. But countless positive actions on the part of pilots, on the contrary, help avert accidents in the event of dangerous situations occurring outside the cockpit, linked to the aircraft or its environment.

In coming decades, with communication links between air transport players steadily improving, significant changes can be expected in flight control distribution, i.e. between "human and machine" / "aircraft and ground", with at least one onboard pilot being maintained on commercial airliners until 2050.

Using quantitative information derived from observations made during commercial flights, we will assess potential safety improvements to flight control for two-pilot onboard crews, taking into account expected progress in the various fields of automation, neurosciences and human-machine interactions and in the areas of meteorology, air traffic control and telecommunications services.

We will then use quantitative safety analyses to tentatively identify the performance and conditions that would need to be met in order to move towards flight control with a single onboard pilot.

5.1.1 Improving flight control safety for a two-pilot onboard crew within a 2050 timeline

Analyses of accident causes and audits on commercial flights generally quantify flight control deficiencies in terms of:

- *flight handling;*
- *omission of action/inappropriate action;*
- *lack of positional awareness – in air;*
- *poor professional judgment or airmanship;*
- *insufficient use of techniques, methods and tools;*
- *deliberate non-adherence to procedures.*

This categorisation highlights the relative significance of levers for improvement such as pilot training and discipline, cooperation between pilots, communication between pilots and ground support services, aircraft systems and the Human-machine interface, among others. This breakdown is used here to define, through engineering judgement, attainable goals for improving flight control safety by 2050.

***Main sources for data on fatal accidents involving crew and corresponding accident rates for the 2002-2011 period** (statistical data drawn from Ref. 2, for commercial jets and turboprops > 5.7 t). The annual number of flights is around $32x10^6$, with 20.5 fatal accidents per year on average ($0.4x10^{-6}$/flight hour). Average flight duration is 1.7 hours. The rate of fatal accidents expressed in terms of hour of flight is therefore ~ $0,4x10^{-6}$.*

Primary causal factors of fatal accidents and their occurrence rate	Worldwide Total > 50%	US and EU operators Total > 50%
Flight handling	14 %	18 %
Omission of action/inappropriate action	12 %	11 %
Lack of positional awareness - in air	10 %	14 %
Poor professional judgment or airmanship	8 %	9 %
Insufficient use of techniques, methods and tools	> 2%	
Non-adherence to procedures	> 2%	

Table 4: Rate of occurrence of primary causal factors in fatal accidents.

PILOT PERFORMANCE NOTED DURING COMMERCIAL FLIGHT AUDITS (Ref. 1)

Observational data drawn from over 300 operational short-haul flights (Boeing 737) and medium-haul flights (Airbus A330) illustrates recurrent crew performance:

- ***Error management*[6]**. *An average of 1.5 initial errors occur per flight, mainly committed by the captain. Once noted and corrected, around 20 % of these initial errors result in an undesirable state of the aircraft…*
- ***Management of threats arising outside the cockpit**: almost 0.8 "**threats to flight safety**" (weather, equipment failure, operational pressure, traffic…) occur on average per flight hour. Overall, flight safety is potentially compromised in 43 % of these cases.*
- ***"Non technical" performance** for task organisation, implementation, exchange of information and situation monitoring; it is homogeneous at a level qualified as "acceptable".*

OPPORTUNITIES TO IMPROVE FLIGHT CONTROL SAFETY

*Similarly to methods used for **detection**, **identification** and r**econfiguration** in the event of a failure, improvements to flight safety must be pursued:*

- *"upstream", during pilots' initial decisions and elementary actions;*
- *at the level of each flight control sub-function, by identifying risks through "human-machine" iterations;*
- *on a global level by the machine, e.g. flight envelope protection on latest generation jets.*

Figure 12 gives an overview of possibilities for improving flight control safety with two pilots on board, as is the case today.

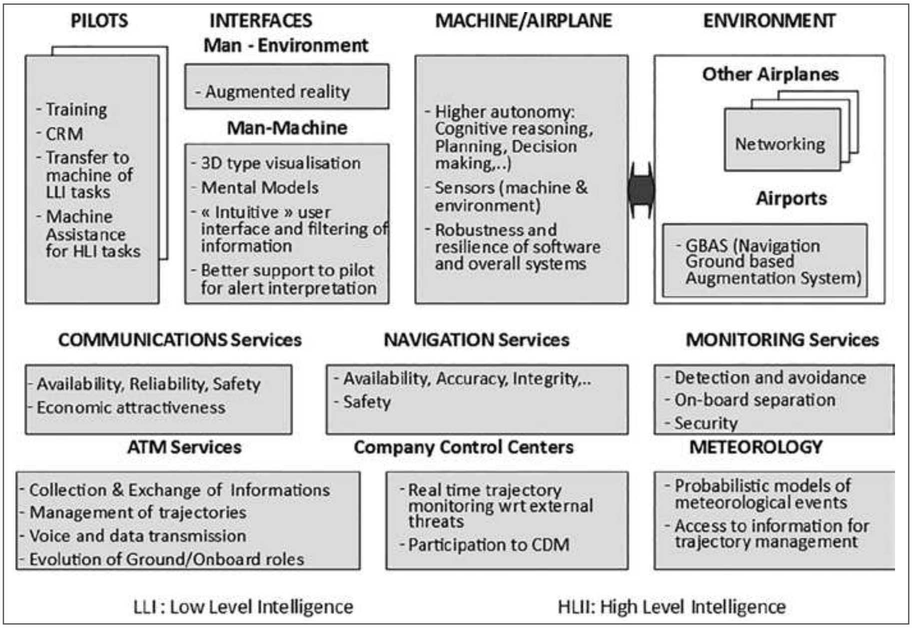


Figure 12: Opportunities for improving flight control safety.

6 *Actions or missed actions on the part of the crew which lead to a deviation from expectations.*

QUANTITATIVE GOALS FOR REDUCING PRIMARY CAUSAL FACTORS OF FATAL ACCIDENTS LINKED TO FLIGHT CONTROL (with relation to North American and EU carriers' achievements).

An attempt is made below to break down the overall goal (defined in Chapter 1) of improving flight control safety by a ratio of three for North American and EU carriers into specific goals targeted at each primary accident cause category.

Figure 13 presents primary cause factors of fatal accidents (as a percentage of the total number of accidents) for the 2002-2011 period along with typical goals for improvement (as a percentage of the number of current accidents). Improvement levels already achieved with latest generation aircraft in the 2002-2011 period show that these global goals are likely to be attainable within two or three decades.

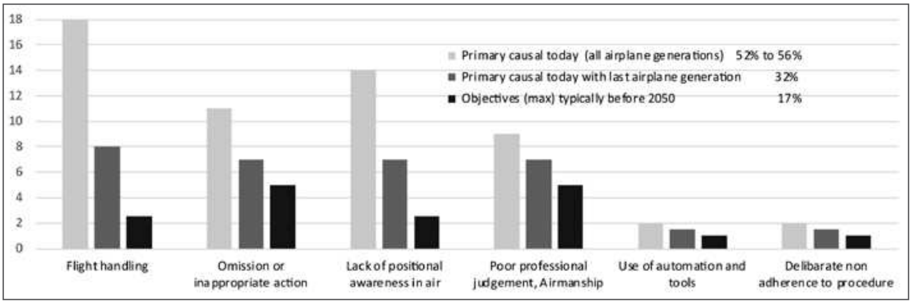


Figure 13: Primary causes of fatal accidents.

5.1.2 Demands on ground assistance for single pilot operations

This chapter considers the standard case for short- and medium-haul flights of a single onboard pilot with no standby pilot on the same aircraft. By using an analytical approach, it aims to avoid the pitfall of potentially erroneous intuition.

In order to meet flight safety goals of a crew with a single onboard pilot, specific measures must be taken to limit the impact of any physiological (and mental) failures on the part of the pilot flying and also to compensate for the degraded performance of this crew configuration (not including physiological failure).

If the impact on the fatal accident rate of changing to a single onboard pilot is to be "negligible" (goal: < $5x10^{-8}$/flight hour), the impact of each contributing factor analysed below should remain lower than (typically) 10^{-9} fatal accidents per flight hour.

PHYSIOLOGICAL DEFICIENCIES OF PILOTS (see Ref. 3).

*Physiological deficiencies can either be **total losses (incapacitation)** or **severe partial losses (impairment) in capacity** with rates observed in real situations of $0.50x10^{-6}$ and $0.25x10^{-6}$ respectively per flight hour. Partial losses in physiological capacity can be more difficult to detect in flight than total losses. As a result, our* *analysis distinguishes between cases of* ***severe partial losses in capacity recognised in real time by the pilot:*** *0.15 x10^{-6} per flight hour, and cases* ***not recognised in real time*** *by the pilot: 0.1 x10^{-6}.*

IMPACT OF PHYSIOLOGICAL FAILINGS

Figure 14 illustrates the sequence of events in the case of physiological deficiency on the part of the pilot, and the associated risk levels (100 % of total physiological deficiencies are assumed here to be detected immediately by automated onboard means).

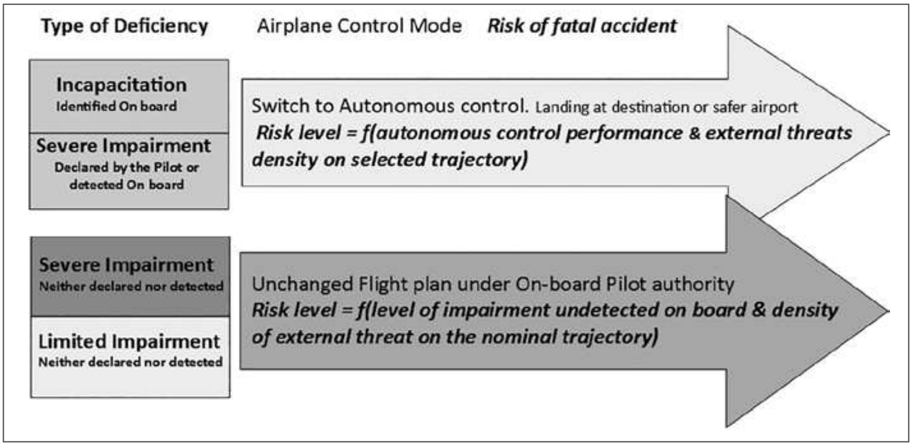


Figure 14: Sequence of events in the presence of deficiency.

The findings show that to ensure the safety level required above, ***in the absence of specific ground support:***

- *there should on average be fewer than 2 % "external threats" that are impossible to manage (without a fatal accident) by pilots suffering from severe deficiency,*
- *the average percentage of "external threats" that are impossible to manage by the automated flight control system should be lower than 0.6 %. Since neither of these two conditions can be guaranteed by 2050, recourse to specific ground support would seem to be a necessity.*

PILOT PERFORMANCE, DISREGARDING PHYSIOLOGICAL DEFICIENCY

Figure 15 recalls typical attainable goals for reducing primary causes of fatal accidents by 2050 (as a percentage of the current rate) for operators in North America and the EU and shows that the drop in flight control performance due to the reduced number of pilots on board might result in an increase of ~8 x 10^{-9} in the number of fatal accidents per flight hour (>> 10^{-9}). It is therefore necessary to provide the pilot with the assistance of a ground operator, for certain flight phases at least, even in the absence of any physiological deficiency.

An assessment of loss of performance when moving from two pilots to a single onboard pilot, with no specific ground support, was made by engineers on the basis of in-flight observations mentioned above.

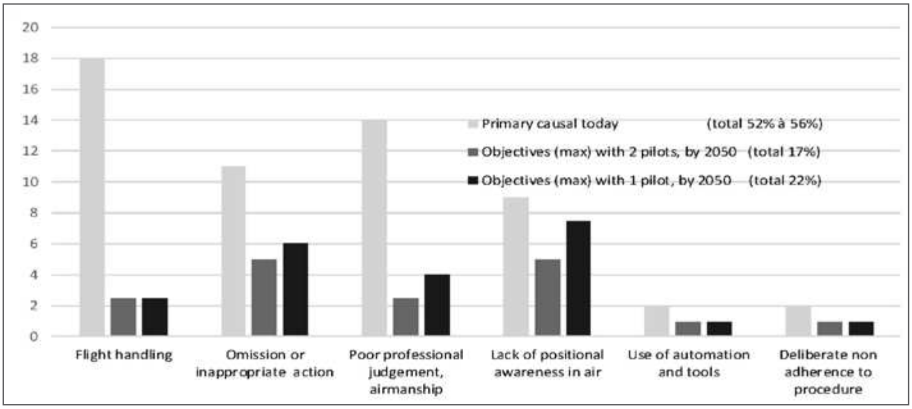


Figure 15: Assessment of loss of performance.

REQUIREMENTS CONCERNING GROUND SUPPORT FOR IMPLEMENTATION BY 2050

Ground support will have to provide the following functions:

- *assistance in detecting physiological deficiency of the pilot,*
- *supervision of and, when necessary, resumption of responsibility for flight control,*
- *assistance to the pilot (aside from physiological deficiency) for critical flight phases.*

REQUIREMENTS CONCERNING THE EFFECTS OF PHYSIOLOGICAL DEFICIENCY

For economic reasons, ground operators should take only intermittent action for each flight.

Figure 16 illustrates potential sequences of events in the case of physiological incapacitation on the part of the pilot.

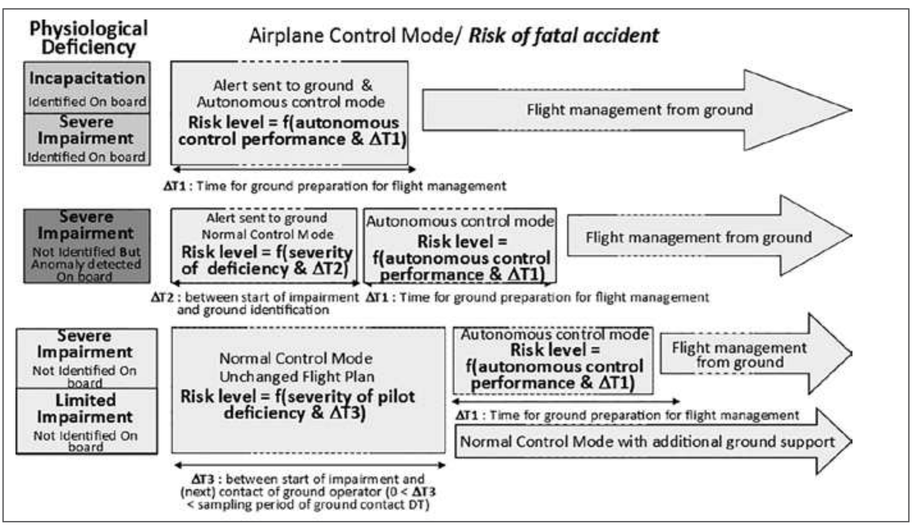


Figure 16: Sequence of events in the event of incapacitation.

An initial, simplified analysis presupposes an even rate of threats from outside the cockpit throughout the flight and on all flights. It is based on two prudent assumptions:

- *in the event of severe physiological deficiency, neither recognised nor identified on board, the pilot could manage (on average) over 80 % of "threats" before ground intervention,*
- *automated flight control in recovery mode will be able to manage over 90 % of threats encountered without any fatal accident within two to three decades.*

It is thus shown that:

- *the sampling periodicity for monitoring the physiological state of the pilot from the ground should be less than ten minutes and*
- *the reaction time on the part of ground support after detection of a physiological deficiency (involving reconfiguration of the communication link and mental preparation of the ground pilot) should be less than six minutes.*

5.2 Illustration of ground assistance in the case of single pilot operation

Here a realistic, uneven spread of threats outside the cockpit is assumed during a flight, along with the need to detect as accurately as possible the extent of the loss of the pilot's physiological capacities.

The setting in place of ground support presented here corresponds to an initial period of operations with feedback from experience over a few years.

VARIATION IN THE NUMBER OF THREATS OUTSIDE THE COCKPIT ACCORDING TO FLIGHT PHASE

Figure 17 gives an overall view of variations in the density and duration of threats for each operational phase for a typical flight of 1.7 hours.

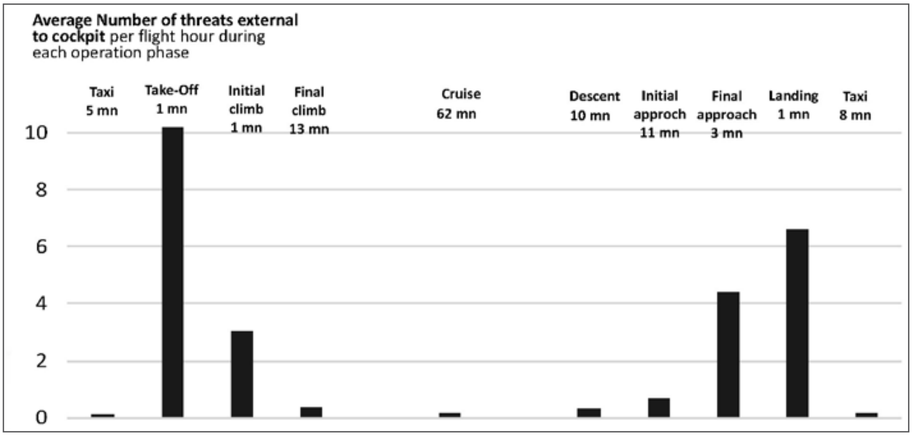


Figure 17: Variation in the density of threats.

The density of ground monitoring of the pilot's physiological capacity should be modulated in line with the density of threats for each operational phase. The analysis shows that this monitoring should have a sampling periodicity of under 0.6 min during the take-off phase, of around 17 minutes during final climb and descent and of around 36 minutes during cruise.

ORGANISATION OF MONITORING BY GROUND OPERATORS

One of the key factors in organising ground support is the capacity of operators – in terms of flexibility, rapidity and reliability – to integrate or update their knowledge of the resources and background of each flight in order to make effective, safe intervention in flight control. Aircraft can typically be monitored from the ground in three ways:

- *by flight;*
- *by geographic zone;*
- *by a mix of these two options, with the accent on geographic zone around major airports. In all cases, ground operators must be pilots and must be affected to aircraft whose generic characteristics are perfectly known to them. The pool of onboard pilots and ground pilots will need to be managed overall by each airline.*

ILLUSTRATION OF SETTING UP GROUND SUPPORT (example of a flight to a major airport)

*An initial ground pilot obtains necessary elements on the specific context and environment of the flight during the flight preparation phase and then monitors the aircraft until the end of the **cruise phase**. A second ground pilot obtains specific flight context elements at the beginning of descent then monitors the aircraft until engines have shut down. During the phases of **take-off, initial climb, final approach and landing**, broadband communication is maintained between the aircraft and the ground support centre in charge of monitoring. The ground pilot provides assistance, and can if necessary take action on flight control. With a latency of < 1 second between the aircraft and the ground, direct communication is possible between the aircraft and the ground.*

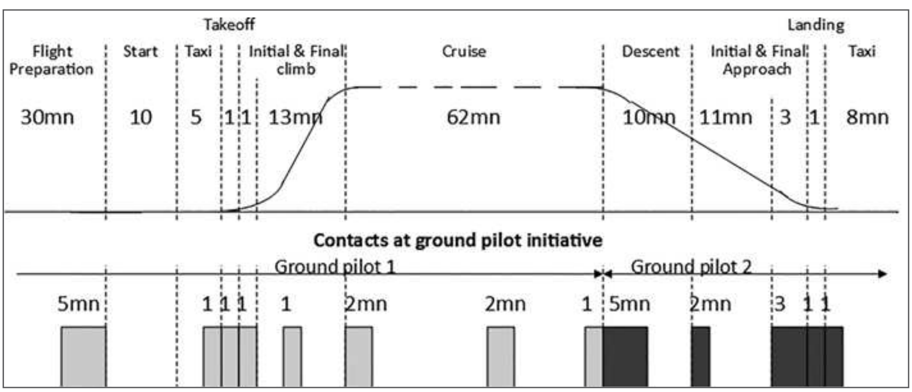


Figure 18: Distribution and duration of ground-air contacts.

Figure 18 illustrates the distribution and duration of systemic contacts between ground operators and pilot for a typical flight of 1.7 hours.

*During the **final climb, initial approach, cruise and descent phases, the ground pilot** establishes periodic contact and assists in the event of "external threats". In the event of severe or complete physiological deficiency of the onboard pilot, this ground pilot:*

- *commands the change to autonomous flight control mode;*
- *reconfigures the broadband communication link (<1 min.);*
- *updates their knowledge of the specific context of the aircraft and its environment (< 2 to 3 min.);*
- *takes over effective flight control (<1 to 2 min.). The communication links introduce a recurrent latency of under a few seconds, compatible with satellite links.*

REQUIREMENTS IN TERMS OF COMMUNICATION LINKS

Here we are concerned with the specific needs of single pilot flight control. The capacity demanded for data flow from the aircraft to the ground, excluding video, remains low, in the order of a few kbits/second. The field of vision and resolution requirements for video transfer during critical flight phases should require less than 500kbits/s, given the kind of video compression technology anticipated by 2050. The availability of communication links must remain higher than 99.8 % during take-off and landing phases.

TYPICAL WORKLOAD OF GROUND PILOT/OPERATORS FOR EACH FLIGHT

In the above illustration, ground operators are active for an overall duration of around 27 minutes (including around 3 minutes for actions relating to outside threats between final ascent and initial approach phases) for a flight involving 155 minutes of onboard pilot operations. This average load increases by a few percent following real or suspected cases of onboard pilot physiological deficiency. One ground pilot could thus manage approximately five flights on average. If operational experience were to confirm the possibility of tailoring ground support to the specific risk level estimated for each flight, a mean monitoring capacity of over eight flights per ground pilot might be envisaged.

5.3 Summary and recommendations

In order to orient research aimed at improving flight control safety, it is important to:

- *intensify flight control performance reports during operational flights in order to clarify the statistical links between pilots' individual and collective performance and each accident cause;*
- *collect data from operational flights with a single onboard pilot (on aircraft with few seats), in order to gain a clearer picture of individual pilot performance, including in stressful situations;*

- *better quantify the probabilities of pilots' physiological deficiency and loss of performance, and test various means of detection;*
- *carry on developing and testing autonomous flight demonstrators.*

Moreover, before analysing the economic advantages of flying with a single pilot on board, it is necessary to look into the general organisation of ground support. Preliminary work would have to go into:

- *analysing the potential strengths and weaknesses of cooperation between the onboard pilot and the ground pilot/operator;*
- *confirming acceptable delays and latencies for telecommunciations;*
- *assessing the capability of ground operator/pilots to support different flights sequentially according to the elected type of organisation.*

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6 CONTRIBUTION OF FEEDBACK FROM DRONES

Author: Alain JOSELZON

6.1 Introduction

Drones are a booming market, with rapid growth in applications and capabilities. Generous research funding has produced mature military drone applications with advanced technologies and operational performances, capable of advantageously enhancing or replacing traditional aviation for various types of mission (surveillance, reconnaissance, guidance, targeted attacks, etc.). This is in its turn contributing to the rapid spread of civil drones for a host of specialised missions. Technology spillovers and synergies between military and civil drones, combined with the ease of implementation and low cost of "small drones", are stimulating the entire drone industrial base and market, with benefits for the aeronautics sector as a whole. As technologies converge, more and more sophisticated drones will approach the capabilities of traditional aircraft.

This boom in drones raises a number of questions:

- *What role do/will drones play in commercial passenger transport?*
- *How can drones be made as useful and efficient as possible, keeping their drawbacks to a minimum?*
- *Could drones be seen as the precursors of a final stage of automated aviation?*

To answer these questions and examine the lessons to be learned from drones within a context of highly automated, interconnected aviation by 2050, it is important to:

- *take into account the gulf currently separating civil drones and passenger aircraft;*

- *assess the potential impact of civil drones on passenger transport;*
- *assess the specific potential contribution of military drones to passenger transport;*
- *anticipate the different uses of drones in commercial airspace;*
- *examine the technological spin-offs of drones for passenger transport.*

The current approach will endeavour to examine the contribution of drones through a study of their different applications.

6.2 Gulf between current small civil drones and commercial airliners

Civil drones currently in operation or under development are distinguishable from commercial airliners by their size and their missions: unlike aircraft, transporting a commercial load is only one of many drone missions, indeed their carrying capacity is very limited. Drones mainly act as vectors in the collecting and processing of data, images and measurements used for diagnostic and decision aids, within an overall set of services offered to customers. We are very far then from ***the characteristics, missions or constraints governing the use of large drones in commercial aviation, particularly in terms of reliability and safety requirements****.*

6.3 Links between issues facing current drones and commercial air transport

Despite the gulf referred to above, small drones cannot be ignored within the air traffic system since they can interfere, whether accidentally or deliberately, with other aircraft. With many cases of near misses already reported, drones can be seen as a problem requiring a solution. ***Two crucial factors determine successful insertion of drones into air traffic: optimised sharing of airspace and effective detection-avoidance systems****.*

6.4 Direct impact of the "drone phenomenon" on passenger air transport

A study of the hypothesis of moving from a two-pilot crew today to a single onboard pilot or even no onboard pilot in future air transport has shown that while a reduction in the number of pilots is likely to cut operating costs, probably without any conspicuous impact on the main economic forces at play and the market, at least one pilot is likely to remain on board commercial passenger transport within a 2050 timeline, for reasons of safety. ***Adding to this the huge gap that exists at present***

***between civil drones and commercial aircraft,* passenger transport drones look very unlikely by 2050*. The direct impact of the "drone phenomenon", then, is limited to the risk of conflicts between drones and air traffic as a whole, with repercussions for all regulatory and safety aspects*.**

6.5 Specific potential contribution of military drones to passenger air transport

Military drones are closer in relative terms to commercial airliners than to today's small civilian drones, because of their size and sophistication as well as the specific requirements of demanding missions and conditions of use in hostile environments: performance (range and autonomy in particular) and resilience to physical or cybernetic attacks. However, a study of incident/accident reports from operational military drones shows that their reliability is markedly lower than that of commercial aircraft.

The nEUROn[7] unmanned combat air vehicle holds some interesting lessons for civilian drones, notably concerning insertion/integration, high level automation algorithms, the place of humans in the loop, mission autonomy, command/control technology validation and a backup mode to ensure the safety level.

The potential contribution of concepts and technologies developed for the military in increasingly sophisticated large-scale demonstrators will be reinforced by the large number of shared issues and the high level of military R&D investment.

6.6 Use of "aeronautics airspace" by drones within a 2050 timeline

FREIGHT TRANSPORT

Freight represents a sizeable proportion of air traffic. Despite a lower growth rate than passenger transport, it is still expected to represent a significant share of air transport in the future.

While passenger transport by drones is unlikely to emerge by 2050, the looser constraints resulting from unmanned flight could well encourage the emergence of specific airframes for freight transport. A comparative analysis should be carried out to balance out the following aspects: the operational flexibility of aircraft transporting

7 nEUROn, a French initiative managed by and under the auspices of DGA (the armament directorate-general), which was joined by several European governments and manufacturers, is a UCAV (Unmanned Combat Air Vehicle) technology demonstrator vehicle which was launched in 2003 to demonstrate the maturity and effectiveness of technical solutions. The contractor is Dassault Aviation.

both passengers and freight, the possibility of aircraft conversions, the savings achievable due to less strict regulations and the new market opportunities created by drones, the safety requirements and finally the implications of an optimised fleet of freight aircraft. ***A change of paradigm cannot be ruled out, with drones capable of carrying freight in conditions meeting both safety and economic concerns****.*

Applications involving ***short-distance transportation of goods*** *are not out of the question either.*

PRIVATE PASSENGER TRANSPORT

Short-distance applications (individuals/families, leisure/business) *could benefit from the emergence of drones with entirely autonomous control.*

COHABITATION WITH PASSENGER TRANSPORT

Given the different drone applications mentioned above, there could be major changes to aviation airspace by 2050. Cases of drone interference with passenger transport around airports will be frequent, requiring regulation and protections. Requirements in terms of safety and reliability will have to be met, with similar challenges to those involved in any attempt to reduce crew members (e.g. response time for communications), especially since the safety rate of air transport must be enhanced by 2050. The risk of a crash-landing (damage to persons and goods) will have to be covered. Solutions inspired from military applications, such as pre-programmed flight paths, could offset certain constraints. As a general rule, ***any use of drones for future transportation will require a level of operational reliability and safety on a par with that of crewed aircraft. Overall cost-effectiveness will have to be confirmed. In the current, rapidly evolving context, given the limited, speculative information that is available for the long term, it is difficult here to produce in-depth analyses of safety and cost-effectiveness and to closely examine concrete scenarios****.*

OTHER APPLICATIONS

There is significant potential in the area of atmospheric telecommunications relay, observation (weather, science, agriculture, vegetation, monitoring, etc.), measurements and experiments in the atmosphere.

TECHNOLOGICAL AND METHODOLOGICAL SPIN-OFFS FROM DRONES FOR AIR TRANSPORT

Many spin-offs can be expected for air transport from small drones due to their rapid technological progress, ease of implementation and low cost in part due to military applications. Informing areas as varied as design, methodology, technology and operations, such spin-offs are bound to proliferate with the upsurge in drones (in terms of number, size, diversification, sophistication, equipment, automation, autonomy and systems). This will enhance knowledge in areas with shared issues (autonomy, human-machine interface, insertion into airspace, detection and *avoidance, systems and software assessment, reliability-safety analyses, risk assessment, etc.) and enable pre-developments. Drones can provide key solutions, for instance, on how to integrate more highly automated, interconnected aircraft into traffic (with a certain autonomy), since this is one of their own priority issues. This would particularly apply to detect and avoid systems (concepts, sensors, data processing, functioning, etc.). Experience gleaned from drones can help with the fundamental question of how to make a non-cooperative aircraft cooperative by means of 'detect and avoid' systems, together with other technologies linked to data processing, signal exchange, etc. Drone solutions to questions of signal bandwidth can also provide useful analogies or transpositions to other aircraft.*

POSSIBLE EVOLUTION IN THE DIRECTION OF LARGE CIVIL DRONES BY 2050

Our (non-comprehensive) analysis of positively and negatively impacting factors, although unable to take into consideration the many interconnections, nonetheless confirms to within a certain margin for error the fact that large drones are extremely unlikely to significantly participate in civil air transport within a 2050 timeline. Freight drones are not ruled out within this timescale, as long as certain obstacles – to do with reliability-safety-security, technology, operations, regulations, economics and psychology – are overcome. ***Drones could nonetheless play a role in pre-development of solutions***. **In terms of safety**, *which must be one of, if not the crucial factor, the situation is summed up in Figure 19 (see following page), in which the asymptotic trend in current commercial aircraft accident statistics, together with the trend in the safety level of drones (RPAS), predicted to improve progressively given the prospect of possible use in commercial transport missions, are projected into the future. The hypothesis is made of a* **possible** *intersecting of the curves at a date, 20XX,* ***which clearly remains highly speculative****. It is likely that the asymptotic trend displayed in aircraft accident statistics would later apply to drone accident rates.*

If such a change were to come about, it could open up prospects for civil drones within a timeline that remains unclear, in terms of dates and conditions; indeed the speculative nature of this approach must be emphasised.

6.7 Conclusion

Small civil drones are currently far removed from passenger transport airliners and their ***direct impact potential*** *in this sector is limited to collision and other interference risks. Moreover, in order to ensure the harmonious development of drones, solutions would need to be found for technical, regulatory and societal barriers. The fact remains that civil aviation is on the cusp of* ***wide-ranging changes, with the advent of increasingly sophisticated, automated systems. It is important not to underestimate neither the unforeseen consequences of***

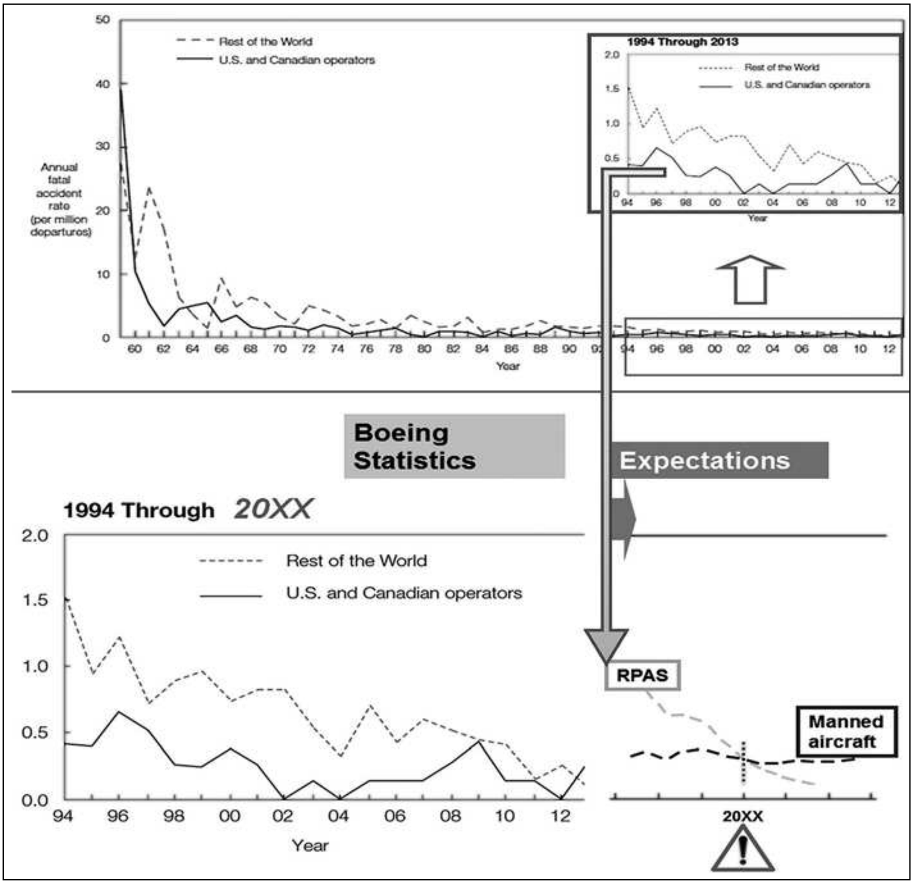

__Figure 19: Drone safety in the future__ (according to C. Le Tallec - ONERA 2014).

such changes, nor the difficulty of introducing technological advances to simultaneously improve safety and efficiency. Those research activities with potential for meeting these challenges, *notably regarding drone proliferation and safety enhancement, must be prioritised.* ***The highly diverse, evolving status of drones, the safety criteria and the lessons learned from experience are some of the critical elements to be taken into account***.

The contribution of military drones, of dual technologies and applications, together with new developments in design, methodology, technologies and operations, the possible use of drones for freight transport in the long term and their spin-offs in research, industry and commercialisation are redynamising the whole aeronautics branch and form an ***ideal basis for future pre-developments in automation, offering low costs, development times and risks. As such drones are playing a unique role as enablers of innovative technical solutions***. *Their momentum is unstoppable, whilst at the same time aviation is moving along a path of greater automation, autonomy and inter-connectivity, which will call for a rethinking of the* *piloting functions of future aircraft. Drone problematics will increasingly intermingle with those of other aircraft, and regulations will be required to integrate them into a coherent ensemble (a process that has also already begun).* ***As time goes by, the initial "gulf" between drones and commercial aviation will narrow, and reflections will be more and more global.***

In-depth research must be done on the many-faceted, evolving question of the potential contribution of drones, in close coordination with other areas of aviation*, in order to* ***consolidate data and analyses and ensure a critical follow-up of the evolutions*** *in the different areas and at the different levels concerned, whether local, national, regional, European or international.* ***This is imperative if we are to refine and enhance our reflections and recommendations****.*

7 CONNECTED AIRCRAFT AND THEIR ENVIRONMENT

Coordinator: Gérard ROZENKNOP

7.1 Introduction

Although the present study focuses mainly on aircraft and flight, one cannot explore the question of more highly connected, automated aircraft without looking at the environment in which they operate. It is in fact, of course, the entire air transport system that will be more connected and automated.

Without claiming to be comprehensive, this chapter therefore examines the main functions of this system - airlines, ATM, communication needs, aviation meteorology, training needs and legal framework – in terms of their inevitable impact on connected aircraft.

7.2 Airlines

Author: Laurent BARTHÉLÉMY

Changes anticipated will have a strong impact on airline operations and organisation.

Without aiming to be exhaustive, the following considerations are tackled below:

- *the exercise of authority onboard the aircraft;*
- *the creation of the "ground pilot" function;*
- *the role of the OCC and operational communications;*
- *commercial communications.*

7.2.1 The exercise of authority on board

The captain is in a position of authority over the crew and passengers, a position that is officially recognised the world over.

Beyond the main mission of ensuring the safety of passengers, crew and aircraft, the captain is thus responsible for a group of tens or hundreds of people throughout the entire mission. This function takes on its full meaning in the event of incidents (long delays, diversions, situations of onboard tension, sick or undisciplined passengers, etc.).

Given the prospect of a single onboard pilot, full checks should be made on this person to ensure they have the necessary mental and physical capacity to perform their mission to the full, or to delegate all or part of it to another crew member, whose profile and location would have to be defined. In the much more futuristic hypothesis of fully automated flight or flight handling from the ground (with no onboard pilot), this need for authority still exists, and would be entrusted entirely to a crew member, who does not possess the natural authority of the captain.

CREATION OF THE "GROUND PILOT" FUNCTION

Scenarios involving a reduction in the number of pilots on board always entail the creation of technical ground support capable of standing in for the pilot in the event of incapacitation. In the vast majority of cases, the role of these ground pilots will be to provide technical assistance to the onboard pilot for those flights (five for example) they are assigned to monitor simultaneously.

In the case of noted incapacity of a pilot in flight, the decision will need to be taken, according to precise rules, to entrust flight management to the ground pilot, who would then devote all their attention to this flight, taking over flight control. What is envisaged here is the activation of a preset programme for safe return to a designated airport. The ground pilot is not expected, at this stage, to pilot the aircraft like a drone.

The required skills, training and qualifications of these "ground pilots" will have to be set out in detail. These "ground pilots" will most likely be seasoned pilots who have passed a specific additional training module. These pilots will alternate periods on the ground and in the air to maintain their qualification and flight experience.

Airline flight operations will need to be reorganised accordingly. However, negotiations with the pilots are likely to be tricky at each stage of the transformation.

7.2.2 The role of the OCC and operational communications

The Operations control centre (OCC) is the nerve centre for coordinating and monitoring an airline's flight programme. It is the single point of contact between pilots and airline during flight.

Technical progress in communication will considerably enhance ground-air exchanges. The problem then will be how to select information to avoid saturating pilots with a flood of data.

A clear definition will need to be given of the roles of the OCC and the ground pilot in all exchanges with the aircraft. The ground pilot will have to be in close proximity (in both geographic and communicational terms) to the OCC and will need to work in close collaboration.

7.2.3 Commercial communications

The proliferation of Internet access onboard is opening up a whole new area of exchanges with passengers. It gives airlines the opportunity to enhance customer relations but also raises certain safety issues which must be dealt with. And once passengers are equipped with these communication facilities, crew members are unlikely to be deprived of them. Regulations will then have to be drawn up governing the use of such communication services to prevent them from becoming a source of distraction or disturbance.

7.3 Air traffic management (ATM)

Author: Dominique COLIN de VERDIÈRE

The functions of ATM – planning, separation, sequencing and informing – will not change; what will evolve is rather the role of the players involved – pilots, airline Operations Control Centres (OCC), ground pilots and air navigation services linked to automated systems.

The ATM system will be trajectory-based, focused on developing exchanges of information between all players and enabling collaborative decision-making (CDM) that takes account of all players' needs, as opposed to unilateral decisions.

Greater connectivity and automation in aircraft will impact ATM in terms of organisation. By making information widely available, new patterns of task distribution will become possible. For instance:

- *the geographical link between air traffic services and their area of responsibility could be severed due to delocalised communication and monitoring facilities and the increasingly virtual nature of centres;*
- *distribution of ATM services according to geographical sector or airspace volume could be replaced by responsibility for a flight or for a group of flights over much wider areas, which is more effective in terms of both ground resources and flight path optimisation;*
- *in certain circumstances, delegation of separation to the onboard pilot or automated systems (Airborne Separation Assistance System-ASAS) could also increase the system's performance.*

The development of onboard automated systems, such as those used by drones, should modify ATM operation en route as well around airports. These systems will have the goal of improving the efficiency of flights and safety and will relate to:

- *more accurate flight path management in four dimensions linked to more precise weather models;*
- *improvements to anti-collision systems and the advent of detect and avoid systems for obstacles or non-cooperative aircraft;*
- *taxiing;*
- *data-link services (which will be introduced sooner or later!!), although these leave an important role to the onboard pilot.*

The networking and standardisation of information provided for in the SWIM concept (System Wide Information Management) will facilitate automatic sharing of flight path data and aeronautical and weather information.

These developments raise questions concerning the evolution of the ATM system:

- *What new distribution of roles and decisions between players, supported by more highly automated, connected systems, would make ATM and air transport more efficient?*
- *What operating modes could emerge from wide-ranging interconnectivity?*
- *How to effectively integrate aircraft with different capacities into the same airspace or the same aerodrome?*
- *What conditions would need to be met for ATM procedures to be automated and which onboard automated systems would facilitate such an evolution?*

7.4 Communication needs

Author: Luc DENEUFCHATEL

One of the main constraints on operating a connected commercial airliner by 2050 remains the capacity to exchange vital data between the aircraft and its operating centre (including the position of remote pilot).

Taking into account the critical nature of information exchanged and the need to ensure the aircraft behaves identically to a manually controlled aircraft, the specifications for communication systems will inevitably be demanding. Such requirements come under the broad heading of quality of service. Quality of service can be described via the following parameters:

- *latency of connection (requirement applicable to the entire transaction between the ground and the aircraft which should be able to be guaranteed to a target of a few seconds at the most);*
- *security of connection (to avoid retransmissions that are incompatible with the requirement of latency);*
- *availability of connection throughout the mission, calling for several levels of redundancy and, perhaps, for two active, differentiated connections.*

Needs in terms of bandwidth should not be too high: needs already expressed by drones give a reasonable idea of the requirement in terms of data exchange. It *should be noted that not all exchanged data has the same criticality and thus the same requirements in terms of quality of service.*

The current state of the art in relevant technologies would suggest that a radiocommunication system (or systems) capable of such performances could be produced today.

Nevertheless, the largest difficulty is both technical and regulatory: it concerns the availability and adequacy of frequency bands in the electromagnetic spectrum. The regulatory aspect presently results in the use of frequency bands known as "Safety of life" that belong to the aeronautical mobile service. These frequency bands are allocated on a global basis and are already extensively used, in particular in zones with heavy traffic (Europe and the United States). It is thus difficult to utilise the existing spectrum without experiencing its drawbacks, namely having to share it with other critical services for flight safety. Another problem stems from the juxtaposition of onboard systems (very limited distance between antennae).

There is thus a strong limitation on spectrum resources, with little hope today of achieving new "Safety of life" frequency bands, except in the higher bandwidths such as the Ka band. These frequencies however are limited in terms of link budget and thus of operational cover.

Work underway in the area of ATM within the SESAR programme clearly identifies the need for new communication links via "Safety of life" bandwidths. The constraints above were also identified, but at this stage the feasibility of a radiocommunication system sharing the same frequency band with other services critical for navigation and monitoring (problem of interference on aircraft mentioned above) has not yet been proven.

From an economic point of view, it is worth noting the probable requirement, to achieve the necessary availability, for two independent links, functioning simultaneously. This requirement will result in additional equipment costs for the aircraft (and the associated ground segment) and extra service costs.

Greater automation and connectivity in aviation depends entirely on spectrum resources and secure communications. Clearly the specific needs of connected aircraft will require much greater bandwidths than today. This problem of spectrum availability is therefore critical, especially since aviation lacks the weight of other sectors in the competition for access to the spectrum.

Safety goals impose a separation between regulated services (ATM) and non-regulated services, for which standard solutions from the wider world can be used. For aviation, particularly in dense airspace, very high demands are made on communication means (latency, capacity, security, availability), since they are directly linked to flight safety. There is no single optimal solution, but there has to be a limit on the number of different technologies used because of the need for systems interoperability.

The system must be capable of resisting all types of interference. While safety is paramount, cybersecurity is equally so.

Much work remains to be done to lay down detailed procedures for single-pilot operations with a remote ground pilot, to redefine the roles and responsibilities of the various players, to elaborate regulatory requirements and to clearly identify needs in terms of communications (bandwidth and performance).

7.5 Aviation meteorology

Author: Patrick DUJARDIN

Proper knowledge of weather conditions is vital in order to anticipate adverse flying conditions that might require a change of flight path and also for planning a suitable flight path to reduce the risk of loss of separation between aircraft.

However, a large degree of uncertainty still remains concerning weather conditions in certain situations that are difficult to predict, even in the very short term. The atmosphere is a chaotic system and no error model is valid at all times. Observation of the atmosphere, and consequently weather forecasting, has improved considerably thanks to important technological innovations as well as a huge body of research, in particular stemming from the SESAR programme which will begin operations in the years 2020-2025.

That being said, whatever the quality of weather information (which will never be perfect given its probabilistic nature), what is important is its integration into air navigation systems. Various scenarios are possible, including systems that will go as far as to translate information into impacts and follow up with an analysis to provide the operator with optimal solutions. The formatting of weather information is thus an essential point since it must be provided in an interoperable form.

The availability of information will be ensured by SWIM (System Wide Information Management), but responsibility for its use has not been identified. The role of each player – weather services, airline operation control centres, crews and ATM organisations – remains to be specified.

7.6 Training needs

Author: Philippe CREBASSA

7.6.1 Background

Within a context of evolving technological capabilities, the roles and skills of the men and women who are to use these future systems will be crucial in order to successfully negotiate the transition towards a new paradigm and maintain it in a stable and powerful state.

The human agent, whether user, manager or maintenance agent, will be the link between the technical system and its operational, economic and social environment. Another complication, specific to aviation, will be added to this heightened complexity: the coexistence of aircraft equipped with different systems (with a greater or lesser degree of automation for example) and drones.

7.6.2 What skills for the pilot?

Aircraft and their onboard systems have not ceased to evolve, enhancing both safety and efficiency. Initially, the pilot's resources were focused on keeping to the flight envelope to guarantee safety. But technical breakthroughs and changing functions have now enabled pilots to use their cognitive capacities for a mission more centred on efficiency, i.e. flight management. Research into autonomous separation will once again transform the pilot's responsibilities, as flight handling becomes more autonomous with respect to air traffic control on the ground.

The pilot's profession and skills have constantly evolved. Pilot training has gradually moved from knowledge-based to skill-based training. With greater, or even total automation of aircraft, the crew of ground or onboard pilots will carry out the mission jointly. Industry will need to construct a robust transition plan to set up suitable training while leaving sufficient time for reliable feedback from experience. For this to succeed, the responsibilities, roles and tasks of the various players will need to be anticipated and clearly defined early on in the process, a prerequisite to any new training scheme.

Research into accidents in the past decade has shown the importance of the pilot conserving basic airmanship skills, an aspect that will be all the more important when the aircraft is flown or controlled from the ground. This foreseeable evolution clearly cannot give rise to greater operational risks than at present. Training courses worldwide will have to take account of this.

Another challenge concerns the suitable level of knowledge and control of the system. Are future pilots destined to be simple operators, simple users with no understanding of how the system works? The answer is no: since air transport is a critical system in terms of human safety, pilots will have to be able to understand why and how the system reacts. Already, pilots' skills can sometimes approach the limits of the system. With greater automation, and therefore even more complexity, the issue of the pilot's level of control over operations will be another major challenge. The nature and quality of the cockpit interface, whether onboard or on the ground, will have to be equal to the task.

The final challenge to be met is the maintaining of skills. Functional requirements will lead to the designing of an extremely powerful automatic system. The pilots will consequently have no problem maintaining their skills for nominal and slightly degraded situations, but what about their aptitude to manage crises and other exceptional situations? The success of a highly automated air transport system will *rely on a new training concept, where continuous training will have more importance than initial training and will occupy a significant share of pilot's working time.*

7.6.3 A broader perspective

For highly automated aircraft to be properly integrated into the air transport system, new trades will emerge and others will change as needs for different skills arise. The flight management and traffic management functions themselves will perhaps be completely overhauled to achieve global mission management.

These changes will go hand in hand with underlying trends in terms of technological capacities, namely increased connectivity between subsystems and systems, greater integration between systems (in particular between the ground and the aircraft) and increased complexity. The challenge will be to maintain a minimal level of intelligibility for humans, by skilfully masking the complexity of the system, which already exceeds human cognitive capacities at any given moment.

7.6.4 Future of training

To meet the challenges identified above, the decompartmentalising of training specialities will have to be pursued. While systems will always be designed and developed by engineers, these systems will increasingly be run by operators with hybrid skills.

Training schemes will become multidisciplinary, with cross-cutting exercises and nontechnical, innovative lessons, enabling the pupil to better grasp a situation in its globality and encouraging initiative.

In the long run, a precise definition of an overall, coherent target will be needed to support the transition towards greater aircraft automation. It is only by clearly defining future trades that the path of transition will be reinforced, leading to a new distribution of functions between human and machine.

7.7 The legal framework

Author: Gérard ROZENKNOP

(based on the paper given by Sophie Moysan of La Réunion Aérienne at the AAE conference on 1 & 2 June 2016)

The legal framework laying down the carrier's responsibilities in the event of a aircraft crash is extremely complex, relying largely on international conventions that are extremely difficult to modify, due to conflicts of interest between States.

By 2050, we are looking at a passenger air transport system that is increasingly automated, using ultra-connected aircraft supervised by a single onboard "pilot", and an almost fully automatic freight sector (remotely-piloted vehicles). A few *decades later, passenger transport will probably no longer require an onboard pilot, and might even use fully automated aircraft.*

The current legal framework governing responsibilities in the event of accidents comprises three levels: international, regional and national. Since 1929, the year in which the Warsaw Convention was adopted, regulations have moved towards stricter responsibility for the carrier and greater damage compensation, particularly in the case of physical injuries. The differing expectations of developed countries and developing nations go some way to explaining the current legal framework and the difficulties and delays in moving it forward.

In a nutshell, the legal situation at present is as follows: frontline responsibility of the carrier, not excluding possible responsibility on the part of other first or second line stakeholders. As a general rule, though, responsibility for damages to passengers or third parties on the ground is focused on the carrier, and is established on the basis of either presumed fault or strict liability. Victims can thus obtain compensation without being called on to provide proof of fault on the part of the carrier or a third party.

At an international level, the responsibility of the carrier for damages to passengers is governed by the "Warsaw System" – made up of the Montreal Convention of 1999 (which came into force in 2003) and the Warsaw Convention of 1929 (entry into force in 1933), supplemented by its modifying protocols, which remains applicable to transportation between States not having ratified the Montreal Convention.

The Warsaw Convention instituted a liability cap for presumed fault on the part of the carrier. The latter could obtain an exoneration by proving that it and its agents had taken all necessary measures to avoid the damage, or that such measures were impossible, or by providing proof of fault on the part of the victim.

The Montreal Convention provides for a two-tier liability mechanism:

- *strict liability of the carrier for physical injuries to passengers (including death), up to 113,100 SDR, roughly 160,000 USD, except when the carrier provides proof of fault on the part of the victim;*
- *beyond this, liability for presumed fault on the part of the carrier, from which the latter can be exonerated only by proving the absence of negligence on its part, the fault of the victim, or the negligence of a third party.*

For damages to third parties on the ground or in the case of mid-air collision, few States have ratified the Rome Convention of 1952 (supplemented by the Montreal Protocol of 1978) so its reach is quite limited. Consequently, damage caused on the ground falls mainly within the domain of national laws, which are very disparate, even within the European Union (EU). Within the EU, Regulation No.785/2004 compels carriers to subscribe to public liability insurance with regard to third parties for a minimal amount per accident, determined for each aircraft according to its maximum take-off weight (MTOW).

Strict liability or presumed fault on the part of the air carrier in no way prevents carriers or victims from suing liable third parties or those with partial responsibility for the accident (contributing causes): air traffic control authorities, certification authorities, airframe and engine manufacturers, OEMs, subcontractors, airport, airport service providers, maintenance workshops, etc.

Will the major technological changes expected within a 2050 timeline require changes to this legislative framework? Not necessarily. The international conventions governing air carriers' responsibilities do not define what an aircraft is, and could therefore be applicable to unmanned aircraft as well as to conventional aircraft. Clearly then, the introduction of passenger or freight aircraft by 2050 with one onboard pilot plus a ground pilot will require no modification of current international conventions. On the contrary, it will be all the more necessary to focus responsibility onto the carrier, with strict liability for damage, since technical responsibilities in this new context will be even more difficult to disentangle (in particular increased "cyber" risk).

Changes likely to be brought in by 2050 to the international framework of responsibilities for the carrier are in fact contained in two international draft conventions aiming to modernise and supplement the Rome Convention with respect to damage to third parties on the ground. These texts were negotiated during the International Conference on Air Law (2009, Montreal) and one of them has since been adopted. The drafting of this convention of course followed the attacks of September 11, 2001. It remains to be seen as to how many years will be necessary before it enters into force, if it ever does…

8 KEY AREAS FOR STUDY AND RESEARCH

Author: Jean BROQUET

8.1 Introduction

It is broadly recognised that the best way of ensuring optimal flight safety, at least within a 2050 timeline, is by combining human and machine capabilities according to the general principle that humans and automation should be left to do what each does best in terms of safety and efficiency. Research must therefore continue to focus on improving our understanding of human behaviour and exploring automation.

Further research into mastering highly interactive, complex systems is proving necessary in order to deal with traffic growth by increasing interconnectivity between the different air transport services.

Section 8.2 presents the areas of study and developments AAE considers to be a priority. Upstream research areas to support these studies and developments are presented in section 8.3.

8.2 Priority areas for study and development

Research underway shows that there is plenty of room for progress in flight safety within the current configuration of two onboard pilots.

Obtaining as clear a knowledge as possible of the aircraft's state, position, immediate environment and any adverse weather conditions during the flight will enable us to reduce threats to flight safety at source.

Human-machine interactions can become more operational, especially during unforeseen events, by better understanding and utilising human capabilities for tasks requiring high level intelligence, whilst using the constantly evolving machine for tasks of low level intelligence.

8.2.1 Automating flight control and improving pilots' capacities for intervention

Two aspects of human behaviour in flight control today – one negative, the other positive – explain why it is difficult to making steep improvements to flight safety through greater onboard automation. It is acknowledged that the greater the level of automation, the more difficult pilot intervention becomes when dealing with unexpected, and particularly unforeseen events.

AUTOMATION

Studies underway in industry into "trajectory-based" flight control systems (c.f. Ref. 2.1, B. Nouzille, Thales) represent an approach to automation by which pilots take on the role of managers and decision makers. According to this approach, human-machine interaction should move towards an organisation by "interactive objects" which would enable overall management of functions.

Current developments are generally progressive or additive (c.f. Ref. 2.2, B. Rontani, Airbus) but opportunities for a breakthrough, and even a total overhaul of automated systems, must be seized.

During such developments, it is important to ensure that the pilot's capacity for "positive interventions" is not compromised when automated systems are inoperative.

MAINTAINING THE PILOT'S ATTENTION

Since automation generates a risk of loss of vigilance on the part of pilots, human-machine interactions and dialogue must be facilitated and reinforced (c.f. Ref. 2.3, F. Falchetti, Dassault Aviation).

Technological progress in human-machine interfaces in particular could be used to better display the machine's plans of action. It is vital that pilots grasp the rationale behind proposed or planned actions, so the machine should use approaches that can displayed in such a way as to be clearly understood and interpreted in real time by human operators.

TRANSITION BETWEEN AUTOPILOT AND MANUAL RECOVERY IN THE CASE OF UNFORESEEN EVENTS

All players involved in flight control underline one of the weaknesses of current systems: the automatic pilot can suddenly disconnect in certain critical situations, *potentially causing a "cliff effect" for the pilot (described in chapters 2 and 4). Ways forward (see for example Ref. 2.3, F. Falchetti, Dassault Aviation) include:*

- *the introduction of progressive alarms and initiation of "human-machine" dialogue as soon as negative tendencies or non-nominal situations appear;*
- *improving perception of alarms (c.f. Ref. 2.4, S. Chatty, ENAC) and facilitating their interpretation for a better understanding of the situation. To this end, certain artificial intelligence techniques could soon be implemented in parallel with current systems, but with no direct impact on the machine;*
- *the maintaining of automatic pilot "subfunctions" (e.g. "attitude control") in the event of loss of the overall automatic pilot capability;*
- *machine assistance to the pilot for identifying available resources or spatial positioning or for elaborating potential plans of action…*

8.2.2 Extensions of flight envelope protections and detection of dangerous behaviour or actions on the part of the pilot

Flight envelope protections can now be reinforced, as is the case for certain military aircraft (c.f. Ref. 2.5, Colonel D. Rouillé).

The level of protection in addition to the existing one must be studied in the light of accidents and incidents occurring on latest generation aircraft.

It is vital to find means to detect dangerous actions on the part of pilots – significant disparities with the initial flight plan caused by pilot action for instance.

8.2.3 Use of probability in weather forecasting to improve air traffic management

(c.f. Chapter 7, Section 7.4)

Certain weather phenomena remain very difficult to forecast (Ref. 2.7, J-L. Brenguier, Météo-France). To mitigate the lack of predictability of chaotic phenomena, meteorological offices make "ensemble forecasts" (of up to 24h), to characterise the occurrence probability of a weather risk.

It then becomes possible:

- *to make an automatic analysis of the 4D fields with weather forecasting uncertainty information,*
- *to determine the optimal trajectory before registering the flight plan, then the reference trajectory after take-off, and*
- *to supplement the universal weather alert with dedicated alarms for each flight and enable adoption of an optimal avoidance strategy.*

8.2.4 New role distribution between aircraft and ground and functional control of an increasingly complex air transport system

The commercial passenger air transport system must be able to cope with the challenges of traffic growth and the incursion of drones in its airspace, whether planned or not. Separation between aircraft is gradually being reduced and anti-collision systems with drones and other aircraft equipped with transponders must be automated and miniaturised.

NEW GROUND-AIR ROLE DISTRIBUTION

With a growing number of telecommunications services on offer, flight safety enhancement will be possible by rethinking the distribution of roles between aircraft and ground and by developing a greater capacity for intervention from the ground. Cybersecurity issues will obviously have to be taken into account.

Recommendations made in section 7.2, "Air traffic management", focus on:

- *a study of new models for task distribution between air traffic controllers, airline operations control centres, pilots and associated automated systems, for all functions, roles and decisions;*
- *a study of drone insertion into non-segregated airspace and over airports;*
- *an analysis of conditions required for ATC automation;*
- *a study of conditions and approaches to enable aircraft with different capabilities to coexist within the same airspace.*

FUNCTIONAL CONTROL OF AN INCREASINGLY COMPLEX AIR TRANSPORT SYSTEM, ALLOCATION OF FUNCTIONS

Given our lack of knowledge and imperfect understanding of certain behaviour and phenomena (meteorology for example), humans are compelled to retain a primary role in the air transport system.

Task distribution between human and machine is based on:

- *automation of system functions according to rules transposable into machine actions;*
- *elaboration of procedures for foreseeable human actions;*
- *autonomy of players (mainly human) in problem solving, with coordination between these players.*

The "multi-agent" system can be modelled as a network of functions whose complexity comes from the functions themselves and the links between them. Computer simulation models are capable of creating virtual systems on which to base the analysis and assessment of future systems.

8.2.5 Mastering industrial development of complex systems

Industry must contend with the increasing complexity of global air transport systems as a whole and aircraft systems in particular. They must procure the techniques, methods and tools to:

- *design and develop complex systems that include highly interactive human agents and machines which meet critical requirements in terms of resistance to aggressions, robustness and resilience during their operational life (c.f. Ref. 2.6);*
- *design onboard systems with critical requirements for the detection and identification of failures and the ensuing reconfiguration;*
- *proceed with software specification, development, validation and testing (whether onboard or ground systems) together with verification, validation and certification of the whole system;*
- *monitor integrity throughout operational life, and support evolutionary maintenance.*

8.2.6 Extending role distribution between air and ground: the case of flight control by a single onboard pilot

The case of flight control with a single onboard pilot can be analysed within the framework of changing task distribution between aircraft and ground, taking into account the changing nature of pilots' tasks and the possibility that the "time-constant" may, at least for certain tasks, be lengthened. The areas of investigation were presented in chapters 4 and 5.

8.2.7 Increasingly autonomous flight control

A system of flight control is known as "autonomous" if the "machine" is able to make decisions and act within in a given context without assistance and without continuous human monitoring.

TEMPORARY AUTONOMY IN THE CASE OF FLIGHT CONTROL WITH A SINGLE ONBOARD PILOT

A capability for completely autonomous flight control for a part of the flight would be necessary in the case of severe or total impairment of the pilot or a threat putting flight safety at risk. The number of flights concerned would be limited to a few dozen per year worldwide (see chapter 5).

The technological capabilities to be developed include:

- *entirely autonomous separation, spacing and avoidance of other aircraft, obstacles or weather risks;*
- *automatic decision on whether or not to engage autonomous flight control mode after an analysis of the situation in the cockpit;*
- *fully autonomous flight control until resumption of control from the ground, or landing.*

TOWARDS INCREASINGLY AUTONOMOUS FLIGHT CONTROL FOR SCHEDULED FLIGHTS

The hurdles to be cleared, in terms of technology and regulations in particular, have been identified in the reports quoted as examples: (US NRC, ref. 3 and AIAA, ref. 4), (see also chapter 6, nEUROn project). System autonomy (with no human intervention) requires machines to have capacities of awareness and understanding of the situation and its environment, adaptability and cognitive reasoning that go well beyond what is currently available in aeronautics.

Research topics include:

- *the capacity to control rare, unmodeled situations;*
- *the dynamic adaptation of systems to evolutions (environment, missions, platforms…);*
- *multi-sensor data fusion and its transformation into knowledge usable for decision-making;*
- *knowledge modelling and mental models of exchanges with humans during "human-machine" interactions.*

Progress is also needed in the field of engineering and as regards the verification, validation and demonstration of the safety and security of adaptive systems. The organisation of ground systems must also be tackled, along with legal (see ref. 2.8) and societal repercussions.

8.3 Areas of researchs to support vital studies and developments

The main fields of research required to support studies and developments presented in section 8.2 are briefly described below.

NB: Most experts recognise the promise of artificial intelligence, particularly pattern recognition and artificial cognitive reasoning, for moving towards greater systems' autonomy. However much effort is still needed on a theoretical level before any implementation in the "critical functions" of flight control, which is why this research is not granted a chapter of its own.

8.3.1 Understanding human behaviour and the role of the onboard pilot

Certain constants of human behaviour can be identified, for example in the neuropsychological mechanisms of short-term memory in rapidly evolving operational situations. This has been demonstrated by Jean Pinet in particular (c.f. Ref. 3, Chapter 5).

F. Dehais, ISAE (Ref. 2.15), also underlines the extent to which human behaviour is impacted by tricky situations, where there is a tendency to miss critical information and tunnel attention. Our understanding of this phenomenon could be improved by *combining cognitive psychology, systems' engineering and neurosciences (in particular neuro-ergonomics).*

Analyses of pilots' behaviour in real situations cited by R. Sumwalt, NTSB (Ref. 2.16) show that humans are not very good at monitoring highly automated, reliable systems over long periods. Effective monitoring is compromised by various factors, including overconfidence, boredom, tiredness, operational pressure and carelessness.

Research on human behaviour aimed at improving the safety level of flight control must tackle aspects such as:

- *observation and collection of data on crew interventions which have a positive impact on the situation, and on behaviour between the pilots in the crew;*
- *neuropsychological study of aviation accidents and incidents, in the same way as pathologies;*
- *non-invasive means of measurement of operational behaviour.*

8.3.2 General approach to role distribution between human and machine

OPTIMISING OVERALL PERFORMANCE

The division of roles between humans and machines must meet the general principle recalled in the introduction: to leave up to humans and automation what each does best, for better safety and efficiency.

Performance necessary for flight control can be classified into categories going from "ability for short-term flight handling" to "capacity to react at the expert level when faced with unforeseen factors". The theoretical limitations of the machine are today at the level of "capacities for reaction when faced with the unforeseen".

However the capacity for exchange between human and machine is also an essential element in overall performance. When implementing complex systems, one can come up against the difficulty of making comprehensible for humans the factors informing the choice or decision of a machine. It is thus possible to opt for less sophisticated techniques which have the advantage of offering better possibilities of dialogue with humans.

Investigations underway into fourth generation aircraft pilots' response to unforeseen situations (c.f. A. Lemmers, NLR, Ref. 2.13) are enriching research with data recorded in real situations.

CLEARLY DEFINING THE QUESTION OF AUTHORITY

Chapter 3 looks into the structuring of automation and the position of humans at the top of the decision-making chain of the overall flight control system. Putting general principles aside, the machine must be equipped with certain specific autonomous capacities such as that of implementing protective actions which have not been decided and authorised in real time by the pilot (for example: flight envelope *protection). A dual monitoring thus goes on: humans monitor the machine and the machine monitors humans. C. Tessier, ONERA (Ref. 2.14) underlines the need to clarify the division of authority between pilot and machine:* "Who has control and who decides for what functions, with what means and what data?"*. Ethical and acceptability issues must also be tackled.*

8.3.3 Human-machine interface

Information provided by the machine can be delivered either continuously, in response to an active request of the pilot, or automatically according to circumstance (distress alarm for example). The score obtained for the pilot's attention level is one of the elements governing "reliability" of exchanges.

Interaction tools call upon different resources and skills:

- *technological ;*
- *methodological (software and systems engineering, interactive software) ;*
- *human factors (ergonomics, cognitive or experimental psychology). Detailed attention is paid to the risks of a drop in vigilance or selective attention on the part of the pilot and other effects contributing to poorer performance. Research is going into further improving the visibility of information and alarms by means of new approaches to systems engineering (c.f. Ref. 2.4 S. Chatty, ENAC).*

The machine can also provide "active assistance" to the pilot by observing their reactions (detection of loss of vigilance) and by modifying the display or content of information (alarms…) in order to trigger renewed attention if necessary.

8.3.4 Assessment methods of "human-autonomy" teaming, engineering of human-machine interactions

Automation increases the human-machine performance in the case of an average pilot workload, but decreases performance in the case of a low or high load.

NEED FOR IMPROVING DESIGN AND ASSESSMENT PROCESSES FOR THE HUMAN-AUTONOMY TEAMING

An analysis of recent incidents and accidents (c.f. Ref. 2.9 M. Feary, NASA Ames) confirms that humans will be an important component of the air transport systems for a long time to come; but the roles played by humans will evolve with the increasing complexity of systems.

The processes for assessing the overall system must be improved and engineering models developed to take into account the heterogeneity of behaviour on the part of both humans and physical systems.

WHAT MODELS CAN BE USED AS A BASIS FOR THE ENGINEERING OF "HUMAN-MACHINE" SYSTEMS?

Are humans necessary and, if so, for what tasks and with what requirements? Apprehending these requirements during engineering phases is particularly difficult *because many of them are not "conscious" and only appear late on at the moment of systems development or implementation.*

Human-machine systems engineering generally draws on empirical models since it is not possible to describe human behaviour and physical systems in a homogeneous way.

ENAC (Ref. 2.4, S. Chatty) explores a way forward for engineering based on a mix of cybernetic models and physical or software models, based on "cause and effect" relationships. This approach allows for an analysis of task distribution between human and machine. It is used to support software developments relating to hybrid "human-machine" systems.

Research includes: the modelling of interactive software, the development of suitable languages and software architectures, the certification of interactive components, etc.

8.3.5 Integrated engineering of air transport systems

GENERAL APPROACH

The "multi-agent" transport system can be modelled as a network of functions whose complexity stems as from the functions themselves as from the links between them. Computer simulation models create virtual systems which are used to back up analyses and assessments. So-called "tangibility" criteria are then introduced (with metrics), to translate the possible physical reality and operational credibility of these virtual systems (Ref. 2.10, G. Boy, FIT, AAE).

Human-centred design is based on a knowledge and understanding of three components: people, organisations and technologies.

A STANDARD RESEARCH TOPIC

Arrivals management and Sequencing in terminal area (Ref. 2.11, E. Hoffman, Air Traffic Services R & D, ATM Directorate). This research topic illustrates the possibilities of exchanging and redistributing roles between air controllers, airline operations control centres (which could define priorities between aircraft) and pilots (who could control spacing between aircraft). The tendency appears to be one of standardisation and systematisation of procedures rather than automation.

8.3.6 Mastering developments in onboard systems and software, systems resilience

The relevant research can usefully be mutualised between areas with potential applications such as the automobile, space and nuclear power industries.

SPECIFICATION, DEVELOPMENT AND FORMAL VERIFICATION OF CRITICAL ALGORITHMIC SOFTWARE

The use of formal methods for the development and validation of critical algorithmic software is a matter of active research, not targeted on a specific application area.

In fact, propagation of a method from one application area to another is hampered by the different training needs of the software teams and by the insufficient proofs and validations provided by software methods and tools as soon as the software is placed within a real system. An assessment of methods already used successfully within the framework of other critical applications (for example: method "B" used for automatic underground railways) must be actively encouraged in the aeronautical industry.

SYSTEMS RESILIENCE

Resilience is here defined as the guarantee that the mechanisms and reliability of a system will not be altered by unforeseen modifications to the system or its environment in the course of its operational life. System updates must be performed rapidly and usually remotely for technical and economic reasons. Overall reliability relies on a capacity for intervention that does not impact the "quality" of the software. Wide-ranging research into software engineering deals with concepts, tools, methods and best practices for the design and development of adaptive software. The LAAS laboratory, for example (c.f. Ref. 2.6, J-C. Fabre) develops systems design approaches by which internal mechanisms for reliability are made up of elementary components (software bricks), so that adaptation to changes consists primarily of a modification in the combination of elements.

SYSTEMS VERIFICATION, VALIDATION AND CERTIFICATION

The search for autonomy is an irreversible trend in the search to master increasingly inter-connected systems. New approaches to verification, validation and certification must be developed for automation and also for role distribution and relations between players. These approaches should avert the danger of spiralling costs.

M. Francis (c.f. Ref. 2.12), for instance, puts forward an approach derived from assessment and qualification methods for human operators that consists of a global assessment and qualification of the human-machine system. In this approach, the attributes of intelligent software should include:

- *a certified communication language ;*
- *the capacity to articulate and elucidate the perception and decision chain ;*
- *an interface enabling close integration between human and machine in the course of operations ;*
- *an interface allowing a detailed understanding of the machine's behaviour by aeronautics experts.*

8.4 Summary and recommendations

Research, studies and development must help improve flight control particularly in critical situations.

Barriers to automation must be removed so as to implement flight envelope protections in order to contend with threats such as terrorism, pilot suicide or failure, *for which protections are currently insufficient. Research relating to autonomous flights, whether exceptional or routine, is important for various reasons.*

The evolution of the air transport system towards greater interconnections and interactions, in order to meet the challenge of traffic growth in particular, must be prepared by means of multidisciplinary research which would benefit from broader mutualisation with other critical applications, and from a closer relationship between industry, official bodies and research laboratories.

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9 SUMMARY OF CONDITIONS FOR SUCCESSFUL PROGRESS TOWARDS GREATER AUTOMATION

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***Reminder**: Various scenarios were envisaged in terms of crew composition (see table page 226):*

- ***Scenario 1**: two pilots in the cockpit as today, with an extension of automated functionalities.*
- ***Scenario 2**: for long-haul, two pilots in the cockpit for take-off and landing; a single pilot in the cockpit in cruise (SPC) with ground pilot support.*
- ***Scenario 2b**: like scenario 2 but without ground pilot support in cruise.*
- ***Scenario 3**: single pilot on board (SPO Single Pilot Operation) for short- and medium-haul, with support from ground pilot.*
- ***Scenario 4**: SPO short- to long-haul, with ground pilot support.*
- ***Scenario 5**: SPO short- to long-haul, without ground pilot support.*
- ***Scenario 5b**: no onboard pilot, but a ground pilot. **The latter is judged to be unattainable within a 2050 timeline for commercial passenger transport.***

***Summary**: The following summary is organised according to relevance to the crew composition scenarios. In order to simplify and clarify this summary, we will consider the following families:*

- *crew made up of two onboard pilots, as is the case today for short- and medium-haul, but extended to very long-haul; this family includes scenarios 1, 2 and 2b;*
- *crew made up of a single onboard pilot (SPO) with support from a pilot on the ground; this family covers scenarios 3 and 4;*
- *crew made up of a single onboard pilot (SPO), with no support from the ground, corresponding to scenario 5.*

9.1 Recommendations applicable to aircraft and operations with a crew composed of two onboard pilots

9.1.2 Short-, medium- and long-haul without ground support

This is the present crew configuration, which is assumed to continue until 2050, at least for aircraft with current cockpit design. Greater automation here would meet the needs of enhancing air transport safety (see chapters 1 and 5) and efficiency (operating or purchasing costs, environmental footprint, traffic growth, punctuality, etc.).

► ***Recommendations on the human level***

- *Further improve co-operation between human and automated systems by pursuing studies into applied neurology, neuropsychology and neuro-ergonomics in order to perfect our knowledge of the human operator, not only in crisis situations (accident), but also during nominal brain operation. Encourage co-operation between neuropsychologists, design engineers and operators.*
- *Collect, quantify and analyse data from all flights to constitute data bases and present "everyday" situations where human intervention has a positive impact, as opposed to very rare, critical cases where human under-performance has been revealed. Automated systems should be capable of covering the majority of these common situations.*

► *Recommendations on the rationalisation and extension of automation*

- *In the context of an irreversible trend towards greater automation, apply from the design stage the principle of allowing humans and automated systems to do what each does best, in terms of safety and efficiency. For example, provide humans with more information on which to base a decision to perform a go-around while entrusting automated systems with the task of sequencing and executing the elementary tasks of this go-around (gradual application of required thrust, retraction of landing gear and flaps, control of flight path and speed).*
- *Rationalise and extend flight control systems by developing architectures to ensure that the autopilot function (AP) is constantly available to the pilot (permanent AP), albeit with minimum functionalities (altitude, heading and speed holding). The goal here is to eliminate the "cliff effect" that can sometimes occur when the human pilot resumes flight control following a failure.*
- *Conventional manual flight control, requiring knowledge and anticipation of the natural reactions of the aircraft as well as "airmanship and piloting skills", must evolve to take on the role of designating flight path goals. Flight control inceptors must evolve into goal designators, with an ergonomic, instinctive, accurate utilisation that stands up to the environment of the cockpit.*
- *Improve the human-autopilot interface to enable a more instinctive awareness on the part of the pilot of the present and future intentions of the autopilot.*
- *Include protections in this permanent autopilot to ensure the aircraft remains within its flight envelope and to prevent collisions with other aircraft, land or water.*
- *Better define the conditions under which human onboard authority could be over-ridden by the machine (automatic flight envelope protection extended to preventive protection against incoherent or dangerous behaviour of the human operating in the cockpit at a given time).*

► *Recommendations on the supply of relevant information to the crew in all flight phases*

- *Facilitate the work of the onboard pilot during flight preparation or inflight rerouting for whatever reason (airline, traffic or airport control, weather, anticipation of certain failure scenarios) by transmitting the relevant data or flight plans that have been prepared or modified on the ground.*
- *Ease mental, cognitive processing during rapidly evolving situations by reducing the amount of information to be processed and using directly applicable, concise displays:*
    - flight handling: enable the pilot to better identify automatic reconfigurations and modes without research and in a more intuitive way;
    - navigation: develop 3D displays with synthetic vision to provide the pilot with an immediate, concise overview of the aircraft's place in its airspace;
    - systems' status: improve display in the event of multiple failures affecting a number of systems simultaneously. First present a concise overview of the situation, providing information above all on functions which remain operational and identifying the most urgent actions required;
    - vision: merge the different types of vision (direct vision, enhanced vision (such as infra-red), and synthetic vision derived from terrain databases and aircraft position/attitude), constantly superimposing flight parameters and autopilot intentions/instructions in head-up vision;
    - further enhance the aircraft's situational display when approaching or exceeding the limits of the flight envelope, in particular aerodynamic limits such as angle of attack, sideslip, overspeed;
    - present the energy situation to the crew during approach, displaying forecast points for touchdown and complete stop. (It might be noted that this development is underway and should result in a reduction of the number of the runway excursions, but could also slightly increase the number of go-arounds with all engines operating. It would then be necessary to improve the current safety level of this operation, especially for twin-engine aircraft. Widespread adoption of automatic go-around with adapted thrust and automatic reconfiguration of high-lift devices and landing gear would meet this need.)
- *Improve the reliability of the information required for the correct functioning of automated systems (redundancy, dissimilarity, likelihood algorithms, data fusion); this is particularly applicable to airspeed information, height above the ground, information necessary for systematic automatic landing and, to a lesser extent, inertial information.*

► *Recommendations on the introduction of new functions*

- *Define a recovery mode: apply recovery modes that exist on military aircraft to civil aircraft, in the event of the aircraft finding itself in unusual, extreme situations/positions in spite of autopilot protections. The "instantaneous" recovery mode must allow for resumption of stable flight conditions on a simple action by the pilot. And, in the event of the pilot failing to place the aircraft in recovery mode (for example "Lack of positional awareness in flight" with pursuance of a distorted representation), consider automatic triggering of the recovery mode.*
- *Develop, enhance and generalise automatic collision avoidance functions, whether collisions with other aircraft or with the ground. To this end, exploit interconnectivity and data bases. Define the respective roles/authorities of the human pilot and automated system in triggering avoidance manoeuvres.*

► *Recommendation for improving flight data collection*

- *Given the drive for greater air transport safety, it is no longer acceptable to leave accidents unexplained due to nonrecovery of recorded flight data. A global system to emit, transmit, collect and record flight data on the ground should therefore be set up, to analyse and elucidate the circumstances leading to accidents. Since band-width limitations are foreseeable, flight data emission should be conditional on detection of abnormal conditions (extension of the system being set in place for aircraft position to all flight recorder parameters).*

► *Recommendations on meteorology*

- *Optimal knowledge on board of weather conditions for the whole flight path is vital for improving the safety, efficiency and comfort of air transport. To this end, the following recommendations are issued:*
    - improve fusion of weather data from different, multinational sources;
    - use aircraft as data sources (flying sensors), transmitting such data to the ground and combining it with previous data;
    - broadcast the real-time, integrated weather situation to aircraft during the whole flight path, including any reroutings;
    - improve forecasting of potential threats from phenomena such as intense convective activity, low- and high-altitude icing, clear air turbulence (CAT);
    - broadcast this forecast to the pilot in real time so that they can take measures to avoid the zone or to reduce the harmful effects of such phenomena on the flight or the passengers.

► ***Recommendations on systems validation***

Improve, develop and implement new ways of designing, developing and validating systems of increasing complexity interfaced with the human operator.

The goal is twofold: to circumvent/eradicate human deficiencies in increasingly complex automated systems and to specify, develop and validate design principles and operating and co-operation protocols that take account of Human Factors requirements and principles.

In order to do so:

- *compile catalogues of normal and exceptional cases based on experience and extrapolation, while developing the means to validate co-operative situations between aircraft and ATC/Met office/OCC;*
- *given the growing use of algorithms known as "Artificial Intelligence", look into the methods and means to ensure their validation. This is a prerequisite to their application to functions critical to safety;*
- *extend simulation means (by developing and generalising interconnectivity) and accelerate their use, mixing pre-set test scenarios with random ones and exposing automation to "hostile" testers to uncover any fault ("hackers") in the systems being validated.*

9.1.3 Very long-haul

Here we consider flights of over eight hours with a crew made up of only two pilots. The take-off, climb, descent, approach and landing phases are carried out with the two pilots in the cockpit. During cruise, each pilot would take it in turns to rest in a specially fitted out crew rest area (with fast, direct access to the cockpit). The pilot not at rest would then be alone in the cockpit (SPC: Single Pilot in Cruise). If an unforeseen event were to occur, the pilot at rest would be woken up to join their colleague in the cockpit. The time needed once the alarm has gone off for the pilot at rest to reach full capacity to analyse and deal with a situation is put at 15mn.

NB: this scenario is different from the present one in which one of the pilots in the cockpit is authorised to "nap" during cruise, whilst remaining in their seat.

The recommendations put forward are those already given above for a two-member crew on short- and medium-haul (see paragraph 9.1.2), with some additional recommendations to make this scenario possible. It becomes necessary for instance to detect any total or partial loss of physiological capacity on the part of the pilot who is alone in the cockpit and to ensure the autonomy and the safety of the flight for the period before the pilot at rest can resume control of the flight.

► ***Recommendations for design***

- *Design installations that enable proper rest, with effective communication facilities and fast, direct access to the cockpit.*
- *Develop systems to monitor the activities of the pilot in function so as to detect:*
    - most human deficiencies;
    - hypovigilance and somnolence;
    - partial loss of physiological capacity;
    - total loss of physiological capacity.
- *Appraise as accurately as possible the minimum requirement for reliable autonomy in cruise (autopilot and its protections), factoring in the time needed for the pilot at rest to resume control of the situation.*

► ***Organisational recommendations***

- *Define the monitoring that will be carried out by the ground (OCC) or by other human operators (cabin crews, air traffic control, etc.) and identify the periodicity of this supervision.*
- *Set in place operational protocols regulating the rest period of the second pilot.*

9.2 Recommendations applicable to aircraft and operations with a single onboard pilot supported by a ground pilot

This family of scenarios includes aircraft operated by a single onboard pilot supported by a ground pilot thanks to good connectivity. All tasks currently entrusted to the second onboard pilot must be covered using onboard and ground automated systems, proper means of communication and a reorganisation of interactions between players. These tasks include:

- *completing the flight safely in the event of physiological incapacitation of the first pilot;*
- *sharing out tasks in such a way as to make the everyday workload compatible with the capacities of a single person;*
- *monitoring the actions of the pilot flying.*

One might note that in the event of total and irreversible incapacitation of the onboard pilot, it is the ground pilot who guides the aircraft to its destination, after a short phase of complete autonomy required for the ground pilot to gain full awareness of the situation and analyse it. This scenario is likely to be cost effective *only if a single ground pilot is capable of monitoring several flights simultaneously. Lastly, let us keep in mind that these cases of resumed flight control by the ground will remain rare and that a greater challenge is more likely to be that of undeclared partial and/or temporary incapacitations of the onboard pilot.*

Initial research should aim to enhance flight control safety within the framework of a single onboard pilot scenario.

It should aim to:

- *clarify statistical links between pilots' individual and collective performance and the different accident causes through more regular flight control performance reports during operational flights;*
- *give a clearer picture of individual pilot performance, including in stressful situations, by collecting data from operational flights with a single onboard pilot;*
- *quantify the probabilities of pilots' physiological failure and loss of performance, and test various means of detection;*
- *continue to develop and test autonomous flight demonstrators.*

Moreover, before analysing the economic advantages of flying with a single pilot on board, it will be necessary to look into the general organisation of ground support, and in particular to:

- *analyse the potential strengths and weaknesses of cooperation between the onboard pilot and ground pilot;*
- *confirm acceptable delays and latencies for telecommunications;*
- *assess the capability of the ground operator/pilot to take action to support different flights sequentially according to the selected type of organisation.*

The recommendations we make to support these scenarios within a 2050 timeline are those mentioned in paragraph 9.1, supplemented by the following recommendations:

9.2.1 Short-, medium- and long-haul

► ***Recommendations on the human level***

- *Pursue studies and research in neuropsychology in order to better understand, apprehend and quantify cases of total or partial incapacitation of the pilot. Continue systematic analysis of the flights on this basis. Extend this analysis to business flights and aircraft seating fewer than 19 passengers, which are flown by a single pilot.*
- *Analyse the mechanisms involved in situational awareness and the capacity to resume control of the flight in order to determine the minimal duration required for total systems autonomy.*
- *Launch research activity and experimentation to extensively explore the different aspects of co-operation between onboard and ground pilot. Define the competences and ideal profile of the ground pilot (confirm that it should be a pilot with good flight experience). Specify and confirm the assistance that can be provided by the ground pilot when the onboard pilot finds it difficult to understand a situation or the behaviour of the aircraft and its automated systems.*
- *Imagine as of now a new approach to a pilot's career which would tackle training needs and new selection criteria including self-control and stress tolerance, as well as questions such as how to become a captain and how to attribute ground pilot posts (by alternating flight and ground functions? by means of greater experience of the pilots on the ground?). Prepare for a long transitional period during which aircraft with two pilots would coexist with single pilot aircraft.*

► *Recommendations for aircraft design*

- *Develop robots to monitor the actions of the pilot in function, in order to detect total or partial losses of physiological capacity undeclared/unrecognised by the pilot.*
- *Develop robots to monitor the actions of the pilot in function, in order to detect most nonphysiological human deficiencies (including errors).*
- *Develop demonstrators for aircraft that can be fully controlled remotely throughout their mission by a ground pilot. Revise systems safety analyses to factor in the probability of having to resume flight control from the ground. Quantify this probability.*
- *Ease the onboard pilot's workload by enhancing automated controls for configurations such as moving landing gear, slats and flaps, integrated engine/speedbrakes/ground braking/reverse controls, balancing of engine failure… Simplify the selection of radio frequencies, simplify execution of a go-around.*
- *Plan for an adapted cockpit. This cockpit will need to be compatible with the presence of a second pilot during a period of full-scale validation of the single pilot concept, as well as the execution of the procedures of recurrent inflight assessment of pilots.*
- *Set up interlinked validation means to validate all systems, protocols and communications involved in co-operation between the aircraft and the ground (interconnected aircraft/OCC/ATC simulators).*

► *Recommendations on communication means*

- *Decide on needs in terms of:*
    - bandwidth from and to the aircraft: distinguishing between normal cases (simultaneous for all aircraft) and exceptional crisis situations (theoretically simultaneous for a limited number of aircraft);
    - response time (latency): distinguishing cruise from terminal zones;
    - reliability: define need for redundancy according to flight phase and zone;
    - safety: encoding adapted to confidentiality of information, measures against cyber-crime.
- *Preserve if necessary additional frequency band allocations, which could prove extremely difficult.*
- *Set up when appropriate the necessary global communication network(s) and the organisation of the associated service providers.*

► *Recommendations for organisation of airlines and OCCs*

- *Define surveillance protocols to be performed through sampling by the ground pilot.*
- *Define the means for monitoring nominal flights. Define the number of flights to be monitored in parallel by a ground pilot, not overlooking the large variety of types of aircraft and their versions. Refine probabilities (chapter 5) to define the minimum permanent presence of pilots on the ground for a given fleet. Do not forget cases which call for an uneven level of intervention or monitoring by the OCC (fleet with high density of take-offs or landings at certain times).*
- *Define how best to articulate monitoring: by a centralised OCC for nonairport phases and by localised control centres near airports for take-off, initial climb, approach and landing (or by centralised OCC from beginning to end of mission).*
- *Define the OCC organisation protocol when exceptional intervention is required: probably the allocation of two ground pilots to a flight that has to be completed with no onboard pilot. Also consider the possible contribution of a member of the cabin crew during this phase.*
- *If necessary, define the conditions and protocol for resumption of flight control by the onboard pilot after temporary, reversible incapacitation.*
- *Finally, take into account exceptional scenarios such as the closure of American airspace on 11 September 2001, or the occurrence of major natural disasters that can significantly disturb air traffic in an unpredictable way. Examine the possibility of sharing services between several smaller airlines operating the same type of aircraft.*

► ***Recommendations for Air Traffic Control***

- *One might recall that at present, with two onboard pilots, the task of communicating with air traffic control, which falls on the PNF (or "Pilot Monitoring"), is very demanding in dense airspace such as the main terminal areas. It is thus imperative to develop all technical means (for example an optimal combination of vocal and digital messages) and methods of organisation (simplification…) to reduce this workload before envisaging the change to a single onboard pilot.*
- *Prepare for incorporating into traffic aircraft that are remotely controlled by a ground pilot (although this will remain rare).*
- *Develop procedures to allow control of the flight and assimilation into traffic of aircraft that are either manually controlled by a ground pilot or temporarily operating in an autonomous way in the rare cases of incapacitation of the onboard pilot.*
- *In the aircraft/OCC/ATM "triangle", specify conditions for direct communications between OCC and ATM (for the case of completion of the flight by remote piloting, but also in everyday cases).*

► ***Recommendations for taking into account feedback from drones***

- *Feedback from drones, expected to proliferate by 2050, will need to be closely analysed and acted on. This is particularly relevant for scenarios with a single onboard pilot, in the event of resumption of control by the ground. If the recommendations put forward in chapter 6 are followed up on, then solutions tested and validated through drone development – optimisation of the ground operator's control station, procedures for insertion of aircraft into air traffic and protection against cyber-criminality – will be transposable to situations involving incapacitation of a single onboard pilot.*

9.2.2 Very long-haul

In this scenario, the single onboard pilot would be resting during long periods of cruise flight; for these periods, the cockpit would thus be "unoccupied" and the aircraft would fly in an autonomous way, monitored by the ground pilot.

► ***Supplementary recommendations***

All recommendations set out above are applicable, with particular emphasis on communications aspects and the OCC. We think it important to mention two specific additional recommendations:

- *Prepare passengers to accept "the absence" of any human being at the cockpit for long periods of cruise flight (consider substituting in with a member of the cabin crew, regular intervention from the ground pilot, or even a virtual pilot?).*
- *Only consider deploying this scenario once sufficient, satisfactory experience has been acquired with the operation described in paragraph 3.1 (single pilot in short-haul, middle-haul and long-haul without reinforced crew). The 2050 timeline then becomes hypothetical.*

9.3 Recommendations applicable to aircraft and operations with a single onboard pilot and no ground pilot support

This scenario is regarded as very difficult to attain for commercial passenger transport within a 2050 timeline, because of the analysis in the chapter 5 showing that without the presence of a ground pilot, goals for enhancing air transport safety as fixed in chapter 1 could not be achieved.

Looking beyond 2050, it could be considered as long as automated systems have been shown to provide a degree of autonomy to the aircraft that enables safe completion of the flight without human intervention. However, excluding exceptional cases of incapacitation, we consider that in 2050, a single onboard pilot faced with increasingly complex automation will benefit from the opinion of a second human operator on the ground…

9.4 Conclusion

It is difficult to predict which scenario will prevail, but it will probably emerge progressively as new developments are introduced. Air transport will continue to be in a state of permanent change, with solutions often depending on local or regional conditions. The different scenarios will be weighed up by the airlines on the basis of studies carried out by manufacturer-developers, the operators themselves, navigation and other service providers and of course regulators. One can guarantee that blocking reactions will emerge, because of the inherently conservative nature of humans, prompt to take refuge behind the precautionary principle, a trend that *can only be thwarted by a pioneering spirit, permanent dialogue and conclusive demonstrations.*

Nevertheless, if the recommendations suggested in chapters 1 to 8 and summarised in this chapter of conclusions were to be applied, scenarios could be envisaged comprising a single onboard pilot in function by 2050.

Many of them remain relevant even if economic analysis were to reject or delay these scenarios and to maintain the two-pilot crew with which we are familiar a long time to come. They would then contribute significantly to the continuing enhancement of air transport safety, which, along with the economic aspect, remains the main motivation for extending automation in aeronautics.

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8 *Abbreviations used hereafter:*
- *AAE = member of AAE and of CAC;*
- *CAC = external consultant.*

ANNEX 2: TABLE SUMMARISING THE KEY EFFECTS OF THE SCENARIOS ON THE MAIN AIR TRANSPORT FUNCTIONS

Functions \ Scenarios	Scenario 1	Scenario 2	Scenario 2b	Scenario 3	Scenario 4	Scenario 5	Scenario 5b
Onboard pilot (OP)	As today, with extension of fully automated flight	**Long-haul (LH):** 2 OPs during take-off, approach, landing; single pilot during cruise (SPC) **(no 3rd OP)**	**Long-haul (LH):** 2 OPs during take-off, approach, landing; single pilot during cruise (SPC) **(no 3rd OP)**	**Short-Medium haul (S/MH):** 1 OP with rerouting airport less than X mins away	**1 OP for S/M/LH:** -for S/MH: idem Sc.3 -for LH: when OP resting, GP takes control of the aircraft	**1 OP for S/M/LH:** -for S/MH: idem Sc.3 **-pour LH:** OP resting in cruise	**0 OP** (Role of captain to be determined)
Ground pilot (GP)	GP not necessary	**GP monitors in cruise** (reaction time for effective takeover =10 mins)	**No GP**	**GP monitors** during entire flight for S/MH (reaction time = 10 mins)	**GP for all flights** (reaction time ~10 mins, but 2 mins when GP is resting)	**No GP**	**GP for all flights** (rest by means of 2nd GP for LH)
Automatic systems	Automatic during the whole flight, door to door	Idem Sc.1	Idem Sc.1	Idem Sc.2	Idem Sc.1 for S/M/LH	Idem Sc.1	Idem Sc.1
Reliability	Automation retains control for breakdowns with a probability of $p \geq 10^{-5}$/flight hour (AMC JAR25 §1309: minor effect)	+Automation retains control for 10 mins for unforeseen event at $p \geq 10^{-3}$/flight hour in cruise to allow for takeover by GP		But retains control for all flight phases		+Retains control for unexpected event at $p \geq 10^{-6}$/flight hour in all flight phases (same reliability as 2nd OP or GP)	
Air traffic control -Strategic separation -Tactical separation -Sequencing -Authorisations/ instructions	Data-link transmission of changes to trajectory and insertion in FMS after validation by OP. Voice enhanced when necessary	Idem Sc.1* In the event of incapacitation of OP flying during cruise, provision for simple corrective orders to be sent to aircraft controls for 10 mins to allow takeover by 2nd OP or GP	Idem Sc.2 In the event of incapacitation of OP flying during cruise, provision for simple corrective orders to be sent to aircraft controls for 10 mins to allow takeover by 2nd OP	Idem Sc.2 For all flight phases	Idem Sc3 For all missions	Idem Sc.4	idem Sc.4

*Includes means to detect pilot incapacitation. ATC is then informed

Functions \ Scenarios	Scenario 1	Scenario 2	Scenario 2b	Scenario 3	Scenario 4	Scenario 5	Scenario 5b
System for in-flight avoidance of other aircraft and the ground	Alert as today + optional for SC.2 (and following)	Directly modifies aircraft trajectory (avoidance manœuvre) unless pilot flying refuses					
Weather	Updates weather forecasts constantly for ATC, OCC, pilots Recommends changes of trajectory in the case of dangerous events Permanently optimises ranges of forecast according to flight phase						
Communications	Idem today	Constant transmission of main flight parameters to GP during cruise. If incapacitation of OP flying in cruise, transmission to GP of full data within 1 min **(attention - distance!)**		Idem Sc.2 for all flight phases	Idem S3 for all missions + For LH, constant transmission of full flight data while OP is resting **(attention - distance!)**	Transmission of essential flight parameters available for air traffic control **(attention - distance!)**	Constant transmission to GP of full flight data **(attention - distance!)**
Cockpit design	As today with simplified parameter display in the event of rapid evolution of the flight situation **Goal-based rather than parameter-based flight control**			**New cockpit design with fewer controls and permanent indications, more automated communications means + introduction of the final backup selector**			Complete overhaul of role of cockpit
Remarks	Pursuit of recommended research including systematic recording of unforeseen events to set up a data bank to ensure robust future automated systems	Responsibilities to be clearly identified	Idem Sc.2	How to train pilots? Simulators + in flight, maintain role for instructor/ examiner albeit with simplified controls	Idem Sc.3 Pilot becomes more of an observer	Scenario very difficult to achieve by 2050 due to time issues for demonstrating automation reliability	Scenario judged impossible to achieve by 2050

GLOSSARY

AAE	Académie de l'air et de l'espace / Air and Space Academy
AP	Automatic Pilot
ASAS	Airborne Separation Assistance System
ATC	Air Traffic Control
ATM	Air Traffic Management
CAA	Civil Aviation Authority
CAP	Civil Aviation Publications
CAST	Civil Aviation Safety Team
CAT	Clear Air Turbulence
CDM	Cooperative Decision Making
CFIT	Controlled Flight Into Terrain
CRM	Crew/Cockpit Resources Management
EASA	European Aviation Safety Agency
EGPWS	Enhanced Ground Proximity Warning System
EU	European Union
FAA	Federal Aviation Administration
FFS	Full Flight Simulator
FIT	Florida Institute of Technology
FMS	Flight Management System
GP	Ground Pilot
GPS	Global Positioning System
GPWS	Ground Proximity Warning System
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
ILS	Instrument Landing System
LH	Long-haul
LOC	Loss of Control
MTOW	Maximum Take-Off Weight
NASA	National Aeronautics and Space Administration (USA)
NLR	Netherlands Aerospace Centre
NTSB	National Transportation Safety Board (USA)
OACI	Organisation de l'aviation civile internationale
OCC	Operations Control Centre

OODA	Observe, Orient, Decide, Act
OP	Onboard Pilot
PF	Pilot Flying
PFD	Primary Flight Display
PNF or PM	Pilot Not Flying (or PM: Pilot monitoring)
R & D	Research and Development
RE	Runway Excursion
RPAS	Remotely Piloted Aircraft System
SESAR	Single European Sky ATM Research
SPC	Single Pilot in Cruise
SPO	Single Pilot Operation
SWIM	System Wide Information Management
TCAS	Traffic Alert and Collision Avoidance System
UHF	Ultra High Frequency
VHF	Very High Frequency
VOR-DME	VHF Omnidirectional Range-Distance Measuring Equipment

Pursuing its reflections into the future of air transport within a 2050 timeline, the Air and Space Academy (AAE) commissioned a study into the progress of automation in this sector in order to answer two key questions: How to pursue the harmonious development of automation within a 2050 timeline, whilst respecting the twin goals of safety and economy? What conditions must be met in the long term for a modification in crew composition whilst maintaining the safety level?

The Air and Space Academy trusts that this work will assist decision makers in determining the steps that must be taken, using the possibilities offered by automation, to pave the way for a safer, more efficient global air transport system.

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