Cockpit Automation Philosophy

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I – INTRODUCTION

As you know, the civil aviation environment has considerably and rapidly evolved in the past decades. In the 70s, 500 billion passengers per kilometer have been transported; in the 80s, this figure has doubled and in the 90s it has doubled again reaching 2000 billion passengers per kilometer. The cargo demand, in parallel increased at an average rate of 10% per year. This has enlarged the air traffic rate and created severely congested skies.

At the same time, many new airlines have been born, lack of pilot has forced operators to employ young cadets, old aircraft have had to co-exist with new technology aircraft. These factors have created new risks in commercial aviation.

On the other hand, **flight safety** criteria became more stringent; **efficiency** of the flight in all its aspects (fuel cost, maintenance and crew costs, minimum delays, etc…), became a primary concern.

All those new contradictory objectives could not be met on older generation aircraft. New technology, automated system availability have helped aircraft manufacturers to upgrade the pilot's working environment – the cockpit – so as to provide the crew with the proper means to fulfill his role while keeping up with all these new constraints.

The cockpits have changed a lot; they carry lots of automation which modifies the crew behavior during the flight. The crew behavior will be adequately modified, if the pilots keep in mind that:

- **The automation is a complement to man.**
- **The automation improves both flight safety and efficiency.**
- **The automation is tailored and adjusted for man.**
- **Man has to adapt to the existing automation through training.**

II – WHY AND WHAT TO AUTOMATE

When man faces a process, he has to fulfill various functions and achieve various tasks. Very seldom is he able to do so by himself. He needs the help of other men or proper tools.

Recently, new type of tools have been developed, these tools have a certain **autonomy**: they achieve several tasks simultaneously or sequentially on their own, so that man's mind and body are freed from some tasks and available for others. These tools are the **automated systems**.

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Airbus has developed automated systems to play to our strengths and compensate for our weaknesses; in other words, if you look at those strengths and weaknesses, you soon discover where we need automation and where we don't.

Strengths

- Man is very complex, with capacity of both analysis and synthesis; he is a **decision** maker.
- Man has a very **special memory**; he memorizes lots of sensations, past experiences, lots of feelings, lots of processes which he has understood. This special memory builds up his intuition, his discernment and experience in life, essential for him to take a rapid decision. In aviation we call this – **Airmanship**.
- Man has also an **instinct** which enables him to do things naturally. A baby, just born and thrown in a swimming pool, can swim.
- Man can **adapt** to new environments. He does so either **naturally** because forced by those circumstances of life, or by a learning process. The baby getting a bit older will not be able to swim, but it will stand-up and walk.
- Flying is not something natural for man, neither jumping out of an aircraft with a parachute. Yet the initial discomfort or apprehension disappears with learning, understanding, will and experience.

Weaknesses

- Man is **slow to act**. Facing an unpredictable situation, his mind will react rapidly, but the reaction will come with a certain delay. He is a slow manipulator.
- Man is an **inaccurate** manipulator: he does not carry very accurate "internal sensors". So that he has to train a lot so as to build his **skill**, and achieve a maneuver accurately, efficiently and consistently.
- Man is a **non-repetitive** manipulator, since his skill is directly affected by fatigue, pressure or stress.
- Man is **slow for computation** tasks. While computing, his mind is kept too busy to achieve any other task. His mind, indeed, can easily work sequentially, but is weak to work simultaneously when facing multiple tasks.
- Last but not least, man is **unpredictable**, potentially undisciplined; he has a natural tendency to passivity, to loss of vigilance, to some kind of laziness.

Man gets bored with routine and repetitive tasks; he then **forgets**.

Automation can give the best of all worlds, if automation is complement to man. Automation must thus be applied wherever it can do better than man:

> ***Man is best as a decision maker, for strategic purposes***
>
> ***Automation is better for tactical tasks such as:***
>
> ***Consistent and accurate aircraft operation***
>
> ***Fast computation System and Situational Awareness Enhancement***

But automation is not there to challenge the pilot's role and responsibility.

III – HOW TO AUTOMATE IN EACH FIELD OF APPLICATION

III – A) Principle

The aircraft and its systems can actually operate within 3 domains of operation.

- The Green domain is the normal flight envelope of the aircraft, or the normal field of variation of the main parameters which control a system.

The role of the pilot and its responsibility is to keep the aircraft flying in the green domain and to keep the systems operating within this green domain, when there is no failure.

- The Amber domain, peripheral to the green one, represents a potential risk for the aircraft or a system if a major parameter drifts into it, or if a failure occurs.

The role and responsibility of the pilot is to minimize the excursions in the amber domain; should this happen, the pilot must do his it most to fly back into the green domain. The aircraft and/or the system are fully controllable in the amber area; it requires full awareness of the pilot of the growing risks when nearing the amber/red boundary.

- The Red domain is out of the limits of the aircraft flight envelope or of the safe field of variation of the parameters driving a system. In the red domain, the aircraft and/or systems exhibit discontinuous and non linear phenomena unexpectedly which makes the operation most difficult or even impossible and dangerous, and which jeopardises the aircraft and/or system performance.

The role and responsibility of the pilot is to prevent any excursions in the red domain, which is some how forbidden.

The automated systems also comply with the 3 colours domain principle:

- The automated systems strive to keep the aircraft or a system operating within the Green domain despite some potential mishandling of the aircrew. It is **Error resistant**.
- The automated system does its utmost to bring the aircraft or a system back into the Green domain, should the aircraft or a system drift out of the Green domain, and it advises the pilot. It is **Error Tolerant.**
- The automated system warns the pilot that the aircraft or a system gets close to the Red domain; hands it over to the pilot, because the pilot is the one best suited to take the strategic decision on how to recover the Green domain. It is **Error Warning**.

III – B) Automation Applied in Aircraft Operation or Steering

The operation or steering tasks devoted to the pilot consists in controlling the aircraft or a system to required values of a set of parameters:

- for the aircraft itself: pitch, bank, heading, speed, angle of attack…
- for the engine: fan rotation speed N1, engine temperature EGT, …

The automation applied for steering tasks is applied in two ways:

- either it relieves partially, gradually or even totally the pilot from that task; this is typically achieved by the AutoPilot (A/P), or the Automatic Engine thrust control system, also called Auto thrust system (ATHR).

- or it consists in assisting the pilot in safely and efficiently handflying the aircraft or manually controlling a system. Such automated systems improve the way the pilot controls the aircraft or the system within the green domain, and prevents him to violate the red domain; this is typically achieved by the Fly By Wire system of the latest Airbus aircraft, as well as by the Full Authority Digital Engine Computer (FADEC).

Let us review broadly how this works:

- The Autopilot and Autothrust systems relieve the pilot totally from the steering task, so as to allow him to achieve strategic tasks such as overall mission management, overall aircraft system status management, proper decision making whenever unexpected event occurs …
  - The operational objectives of the A/P and ATHR is to operate the aircraft and engines within the green domain. Consequently:
    - they can only be engaged when the aircraft flies in its normal flight envelope
    - they ensure that all parameters are kept within the green domain, despite possible miselection from the pilot, when feasible
    - they disengage when a major parameter gets too close from the red boundary so as to allow the pilot to best react in front of a dangerous situation
  - The A/P and ATHR operate in various modes and to various targets which have been defined so as to accommodate most Air Traffic Control (ATC) clearances, or specific repetitive maneuvers. The pilot is the master of those systems, he is the one who chooses the modes and selects the guidance targets according to ATC clearances, using dedicated interfaces:
    - in case of short term clearances (e.g. fly a heading, a speed, a vertical speed), the pilot selects the required target and mode on the Auto Pilot Interface called Flight Control Unit (FCU). The Auto Pilot operates in selected modes in that case.
    - in case of long term clearances (e.g. fly a Standard Instrument Departure...), the pilot defines the associated trajectory on the Flight Management System (FMS) interface called Control Display Unit (CDU). The Auto Pilot operates in Managed modes in that case.
  - The A/P and ATHR operate under the direction of the pilot, who needs to be provided clearly and unambiguously, with the information required to actively monitor the proper operation of those systems.

- On the other hand, in certain phases of flight, the pilot has to handfly the aircraft or manually control the aircraft:
  - The Fly By Wire computers carry a program called “Control Laws” which actually determine the handling characteristics of the aircraft. Those have been defined so that the aircraft is BOTH stable and maneuverable within the whole green domain, so that the response of the aircraft to pilot inputs on the stick be consistent on all axis while the efforts required from the pilot on the stick be balanced, regardless of the aircraft speed, configuration and centre of gravity. What a comfortable resulting aircraft handling!
  - The Fly By Wire control laws have built in protections in order to minimize the risks of violation of the red domain (which is out of the limits of the safe flight envelope of the aircraft). The protections give full authority to the pilot to get consistently the best achievable aircraft performance, with an instinctive and immediate action on the stick, while minimizing the risks to over control or overstress the aircraft. This aerodynamic protection significantly raises the safety level of the flight.
  - The same principle of protections apply for the engines and the braking system:
    - the FADEC carries an engine anti surge protection
    - the brakes are equipped with an anti skid protection

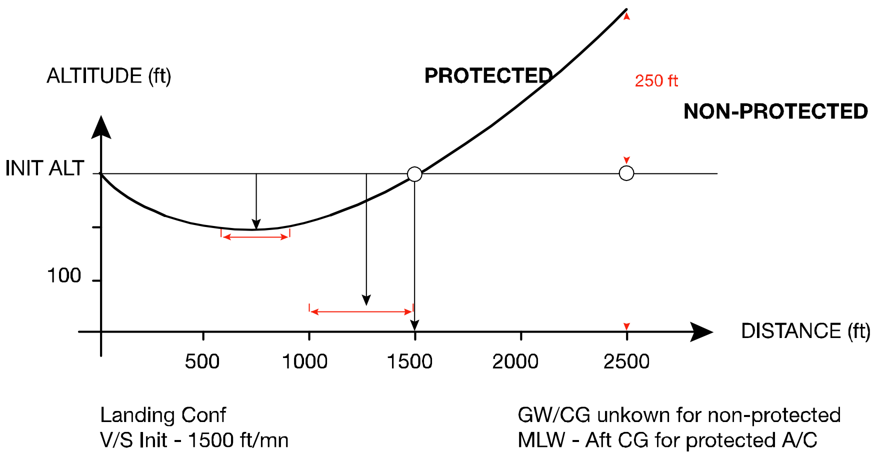
- As a summary, in a standard in line flight, the pilot uses the Auto pilot and Auto thrust systems to operate the aircraft.

  Should an unexpected event occur, those systems will do their best to keep the aircraft within the green domain (e.g. windshear, avoidance maneuver…). If the situation becomes too severe and some aircraft parameters reach the amber domain, a caution is triggered to raise pilot's awareness of potential risks.

  If the situation still aggravates and some parameters get too close to the amber/red boundary, the Autopilot trips off with a red warning so as to give the hand over to the pilot who is the only one to be able to take the best decision on how to fly back towards the green domain.

  However the Fly By Wire protections assist him to best achieve that task; in such a situation, a simple and intuitive procedure allows the pilot to get the maximum available aircraft and engine performance while minimizing the risks to loose the control of the aircraft.

  Yes we can state that automation improves both flight safety and efficiency as materialized by the hereunder graph depicting recovery maneuvers flown by "protected" and "non protected" aircraft coming down dangerously close to terrain.



CFIT Escape Trajectories – Protected versus Non-Protected Aircraft.

III – C) Automation Applied for Fast Computations

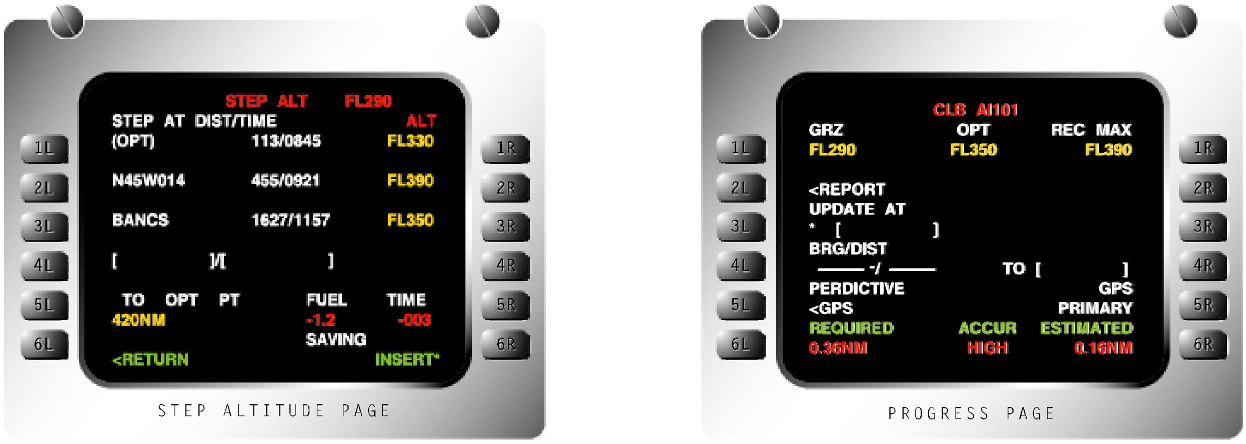
During a flight, the pilot has to concentrate on its strategic task which is to make the right decisions; many of those decisions are the result of a whole set of complex calculations. Most of those computations are given to computers, best suited for that purpose since they are able to achieve lots of calculations accurately and rapidly.

The FMS is the computer which conducts most of the computation tasks such as Navigation, flight planning, performance, optimization, prediction… All those tasks enhance the decision making ability of the crew if the FMS is properly designed.

The FMS has been designed to be a support to the crew, since the various operational design goals were:

- To facilitate the achievement of the listed tasks (navigation…)
- To provide information adapted to every flight phase

- To provide clear, unambiguous, understandable information
- To be consistent with the cockpit environment
- To enhance crew cooperation and coordination



FMS Optimization Results.

The FMS is still only a computer, with no intuition, no intelligence, no discernment and no decision capacity. It needs pilot inputs and interventions to properly achieve its tasks: from this stand point it may be considered as part of the 2 pilot team, with whom the 2 pilots have to communicate.

But the FMS cannot be considered as a reliable and trustworthy copilot since it is merely an operator which works repetitively, consistently and accurately according to a preplanned built in logic.

III – D) Automation for System and Situational Awareness Enhancement

In order to achieve its essential tasks – operate, navigate, monitor and manage the flight our systems – the pilot needs various information to initialize, to control, and to monitor those systems.

This information is handled by various computers such as Data Management and Flight Warning Computers (FWC, DMC) which send them to display units, EFIS and/or ECAM.

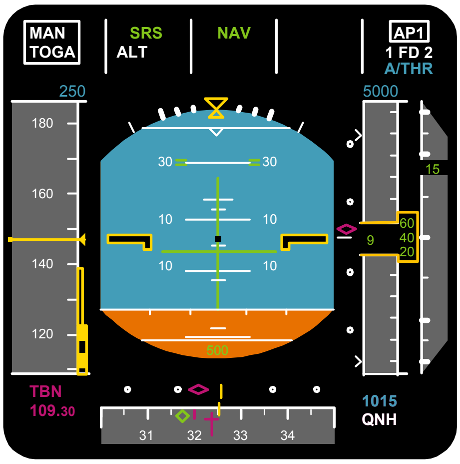
The pilots do not want an overload of information; they wish to be provided with a right selection of parameters best adapted to a given flight phase, and with synthetic type of information when better tailored than analytical ones for a given task.

Consequently, a dedicated display unit is provided to accommodate each essential task the pilot has to achieve:

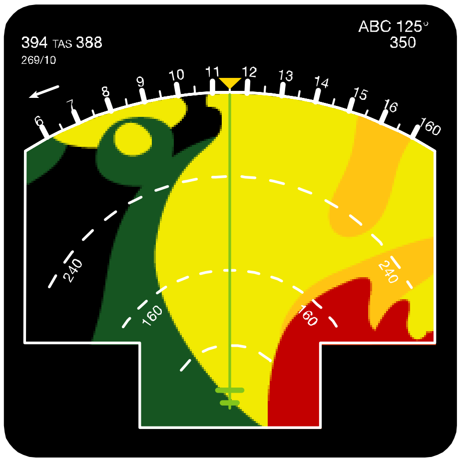
- The Primary Flight Display (PFD) incorporates all the data necessary to handfly or to "autofly" the aircraft.

  This is why the status and modes of the Auto Flight System (AFS) and associated guidance targets are displayed on the PFD.

- The Navigation Display (ND) provides all data related to the navigation task of the crew, consistently with the FMS functionalities and the MCDU display. The ND incorporates also information from various peripherals such as navaids, radar, TCAS, EGPWS… which are so efficient when their display is directly related to the aircraft position, but also to the predicted flight plan.

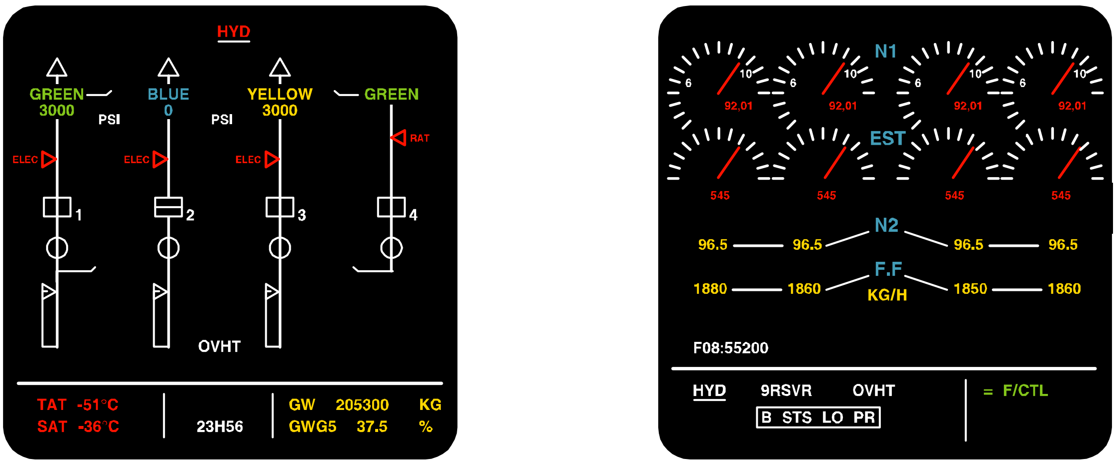


Primary Flight Display.



Navigation Display.

- The Electronic Centralized Aircraft Monitoring system (ECAM) display units provide all data related to the system management task of the crew. Those data are numerous thus properly organized according to the following operational principle:
  - The parameters needed permanently are displayed on a unique field of the Engine and Warning display (E/W-D).
  - The data needed intermittently (in case of a failure for example), or needed in a given flight phase, are provided on the lower ECAM called System Display (S-D), when required.
  - When an "unexpected" event occurs requiring a caution or a warning, the associated data are provided as follows:
    - a cancellable aural and visual caution or warning
    - all data required to analyze the situation in the form of a system synoptic
    - the recommended actions to be achieved by the crew on E/WD
    - the resulting limitations and specific procedures, if any, once the aircraft systems are reconfigured after the failure



Ecam Engine/Warning and System Displays.

All those Display units (DU's) use the same consistent display rules. The automation principle of the 3 colour domains – green, amber, red – obviously apply:

- on the PFD, for the speed scale for example for which the normal flight envelope is lower limited by an amber strip in which it is risky to fly, below which there is a red band where loss of control or at least a severe loss of performance is expected.
- on the ECAM, an amber caution allows for a delayed crew reaction whereas a red warning calls for an immediate reaction by the pilot due to the severity of the situation.

IV – HOW TO ADAPT MAN TO AUTOMATION

- Man has a **tremendous capacity to adapt** when his environment changes. The last century's evolution in many fields witnesses this adaptability:
  - In transport, yesterday distance was the criteria; today, it is time!
  - Yesterday, travel was a luxurious matter; it is part of today's culture!
  - Yesterday, stepping into an airplane was a frightful matter; today it is as simple as stepping into one's car.
  - In communications, the past two decades have witnessed a real revolution which actually merely starts. Satellites, networks, portable telephones … make any information available instantaneously to anyone, and this has become a need.
  - In day-to-day life, the relation in between family members has significantly changed because of the imperceptible invasion in the house of TV, computers, automatic washing machines. While the mistress of the house is in command of a battery of kitchen automated machines, the husband plays chess on a terminal with a friend travelling on the other side of the earth and the children watch a foreign TV program.

This adaptability is **smooth** when the evolution is **slow**, when it has the same "time constant" as man; the adaptability is **tougher** when the evolution is **fast**, even if it leads to a better world, because man, per nature, is **conservative**.

- We pilots are even more conservative than others, because initially, flying **was not natural to us**.

When we first flew, what an apprehension! Maneuvering in three dimensions, pitching up or down, banking, stalling, spinning, made us shiver at first. Watching the outside world from up there made us discover a new world in which, at first, we got lost.

Yet we have **trained** and **learned** how to fly! We developed methods, tools, tricks, to make flying business more instinctive, more natural! These methods, tools and tricks were directly linked to the **existing technology**. They were not mean to remain intangible because everyone knew that they were not perfect:

- Is a radial such an intuitive means to locate an aircraft?
- Is the aircraft symbol the best adapted information to fly an approach?

Location of Aircraft using DRMI.

Yet, we pilots are **reluctant** to change to better pieces of information or to better tools, because we made the old ones intuitive, after a long and sometimes painful training.

- On the other hand, despite all these evolutions, the primary role of the pilot is **unchanged**: complete the planned flight for the sake of the passengers (with more severe safety and efficiency criteria).

To fulfill his role, the primary **functions** of the pilot are **unchanged**: plan his flight, monitor the flight in real time, and take the appropriate strategic decisions.

To achieve those functions, the primary tasks of the pilot are **unchanged: operate, navigate and communicate**. To fulfill all these goals, the pilot has always needed a **team – the crew**.

The emergence of automation into the cockpit has actually **modified the way** the crews have to achieve **their tasks** and **monitoring function**. Consequently, some of the automated systems have to be considered as part of the team.

In a team, each team member has an assigned role; the pilot is the chief, the teamleader! The co-pilot is an assistant to the teamleader, who would fully replace him under extreme conditions.

The pilot and co-pilot can be **efficient** in their respective functions only if they **understand** each other's reactions.

The **automated** systems are merely **operators**! They work repetitively, accurately and consistently according to a built-in logic.

But, they have no intuition, no discernment, no decision capacity. Hence, they should never be considered as reliable and trustworthy co-pilots.

Automated systems being part of the team, pilots and co-pilots must understand their reactions; in other words, they must **understand why** the automated system works in a given way.

Thus pilots have to be trained to know the **why's** of an automated system reactions, rather than to log in their brains all the details of how it works.

- **Training considerations**

  A good training makes flying more instinctive, more natural; this goal is ambitious, but fundamental.

  The pilot must properly and smoothly adapt himself to the automated system through adequate training (the opposite statement being obviously impossible).

  Thus the training shall teach:
  - **The why's**: the understanding of the automated system behavior
  - **The interdependence** of the automated systems
  - **The contributing factors to pilot's errors**

- **Teach the contributing factors to pilot's errors**

  The training must integrate the **lessons** learnt from all aircraft accidents and incidents; some of them have been caused by the misuse or mishandling of automated systems.

  The training shall, therefore, pinpoint the human weaknesses in that field, and procedures shall be defined to avoid them.

  These **weaknesses**, common to all types of automated aircraft, may be divided into four categories:
  - **Lack of proper monitoring**
  - **Autopilot/Autothrust or Flight Director mode misuse**
  - **FMS workarounds**
  - **Data entry errors**

- **Lack of proper monitoring**

  A pilot is poorly suited to be a **passive** monitoring agent: passivity leads to boredom, to lack of vigilance. Thus procedures and in-line training must insist upon **active** monitoring from the pilots:

  - The **aircraft systems** must be **periodically reviewed** on the ECAM so as to detect rapidly on the synoptics, a potential parameter drift or malfunction.
  - The **FMS navigation** must be **periodically crosschecked**, in cruise or TMA (Terminal Area).
  - Any other system must be monitored with the **right cues**: e.g. any autothrust system will be monitored with the energy cues, that is, speed, speed trend, N1, (EPR) command and FMA (Flight Mode Annunciator).

- **Autopilot/Autothrust or Flight Director mode misuse**

  The pilot is the one who commands all those systems; he acts on the autopilot interfaces to select modes and targets, sot that those automated systems work according to the **pilot's intents**.

  Hence, when the pilot commands the autopilot/flight director and autothrust, he must permanently keep in mind those two questions:
  - **What do I want the aircraft to do now?**
  - **What do I want the aircraft to do next?**

  However, a malfunction, a mode reversion, a wrong selection might induce some confusion to the pilot. If those questions are present in his mind (instead of " what does it do? "), he will **rapidly** determine the misbehavior of the aircraft in relation to his own intent.

  If puzzled, he will take control and do it himself.

Consequently, the training must stress upon:

- A **periodic monitoring** of the A/P, Flight Director, A/THR mode and engagement status on the FMA.
- An **immediate take-over** by the pilot (mode or target change, or total disconnection), whenever the aircraft behavior does not match the pilot's intent.
- **Specific scenarios** (reversions, malfunctions…) potentially and realistically confusing the pilot's mind must be defined.

- **FMS workarounds**

The FMS, as any other system in the aircraft, has a limited number of functions. Certain ATC clearances may be a problem for a given FMS; but there is no existing FMS which can match fully all the possible clearances existing throughout the world.

Some pilots have developed **workarounds or tricks** on the FMS to approximate ATC clearances; in other cases, they insert voluntarily incorrect data in the FMS Control Display Unit (MCDU) to achieve a result.

These workarounds require a lot of estimating and keystrokes; furthermore, they may cause serious errors, such as a pilot wrong defined waypoint insertion.

Therefore, the training must firmly state that any system, including FMS, has to be used **within its operating limits**; if the FMS is not designed to achieve a given function, other means are available in the cockpit to do it.

- **Data entry errors**

This type of errors comes up with the emergence of keyboards, MCDU's, etc… But apart from the usual finger errors (due to parallax, wrong selection…), the data entry mistakes may be caused by two other factors:

- **Navigation data base** induced errors: poor coding of waypoint indents, confusion in the name of a waypoint (different indent on the chart, and in the data base), missing data…
- **Figure entry error** (180° error on the inserted bearing).

Consequently, in order to minimize the effects of such errors, the training and the procedure must clearly outline:

- **To systematically crosscheck** a temporary Flight Plan, prior to its insertion in the FMS, using ND plan mode.
- **To know in advance** what, approximately, shall be the result of a pilot input in the FMS (right or left turn).
- **To systematically confirm** with the other pilot any entry on the MCDU.

However, a possible **lack of communication** between the crew members outweighs these four types of contributing factors to errors associated with automated systems.

Crew communication and coordination are the key issues for a proper crew behavior with automation.

The **Airbus Crew Resource Management (ACRM)** focuses on how essential **crew communication, task sharing and cross-monitoring** are to an automated cockpit.

V – CONCLUSION

Yes, **automation** makes it possible for a pilot to fly **accurately, on time, efficiently and safely**, in an even more congested air traffic environment.

All these automated systems have been designed to **complement** man, thus to do what they can do better than man.

In the early days of aviation until the time of the Strato Cruiser, flying an airplane was hard physical work. Pilots had to navigate their flying machines, hand-flying them most of the time. Their main task was to battle against the elements, to soften, to break-in fiery and ardent airplanes. But few of them were flying up there! No slots, no congestion…, and they could and did consider themselves as **lonely** and **romantic heroes**.

Today, air transport is far more complex; the crew has to face many constraints and to achieve far more numerous tasks.

So, the pilot has become the **teamleader**; as a Captain, he has to coordinate and organize all those tasks which will be executed by each member of the team, including the automated systems. Indeed all these tasks cannot be achieved by a single man, even if he is a hero!

Being a teamleader, the pilot has to **adapt** to his team members; he has to **understand** them.

As the boss,
the pilot holds the final decision
using his intuition, discernment and experience
- HIS AIRMANSHIP -