Human-Machine Interaction in Aviation: A Future Threat or Resource

Gerardo De Maria

S. T. A. S. A. (Air Transportation Safety and Environment Care Research Centre) 10, Rome, Italy

Email address
gdm.lab@gmail.com

Citation

Abstract
An efficient mobility is a key issue for the policy makers. Allowing free movement of people and goods is essential for the economic prosperity and sustainable living. Cars, trains, boats, airplanes and space rockets are the means that let differences around the World become wealth. All these systems are recognized as dynamic ones and more are the degrees of freedom, stronger is their tendency to be variable and unpredictable. To rule the operations through these intricate environments and to cope with a continuous efficient problem solving, a reliable arrangement is needed. Safety is the lubricating fluid that gives this complex machine of transportation the chance to work and evolve. The aim of this paper is to analyze the connection between aviation safety and automation philosophy, focusing on human-machine interaction, particularly after the introduction of new airplane building concepts. Automation gave its contribution to enhance safety, but ultimately reveals some threats that must be thoroughly investigated and mitigated to avoid decay in the safety levels.

1. Introduction

An efficient mobility is a key issue for the policy makers. Allowing free movement of people and goods is essential for the economic prosperity and sustainable living. Cars, trains, boats, airplanes and space rockets are the means that let differences around the World become wealth. All these systems are recognized as dynamic ones and more are the degrees of freedom, stronger is their tendency to be variable and unpredictable. To rule the operations through these intricate environments and to cope with a continuous efficient problem solving, a reliable arrangement is needed. Safety is the lubricating fluid that gives this complex machine of transportation the chance to work and evolve. By way for example, modern aviation organizations establish every action of their operations on safety. In fact, every operational procedure is the product of an endless contribution of the manufacturers’ studies and final operators’ experiences (e.g. airlines).

In the following paper three hot aviation topics will be covered: safety, automation and human-machine interaction. We define them as "hot topics", because they are related to the main reason why accidents and incidents happen nowadays: loss of control inflight, named as "LOC-I" or "LOCI".

What is known as "CFIT", controlled flight into the terrain, and runway excursions are the other two main causes of fatalities in aviation of the last thirty years. They are all related to human errors that contribute for a good 70% to the occurrence of these events. The aim of this paper is to analyze the connection between aviation safety and automation philosophy, focusing on human-machine interaction, particularly after the introduction of new airplane building concepts. Automation gave its contribution to
enhance safety, but ultimately reveals some threats that must be thoroughly investigated and mitigated to avoid decay in the safety levels.

This analysis is divided into six main parts:
1. Introduction to the main concepts of the paper and to the theory of dynamic systems;
2. Accident/incident curves through decades;
3. Definition of safety, its role in modern aviation organizations (e.g. airlines), the most modern approach to safety philosophies;
4. Definition of automation, its different levels and the latest technology advancements;
5. Review of human-machine interaction; how it evolved through decades;
6. Outline, throughout the paper, of some possible solutions that can be adopted in a near and a far future to make the human-machine interaction, a pretty intricate one, smoothly works.

Brief reference to dynamic systems

Before starting the analysis of the accident/incident curve, let’s briefly illustrate what system theory is, how a dynamic system work and in which way aviation can be modeled as a complex system.

"Systems theory is the interdisciplinary study of systems in general, with the goal of discovering patterns and elucidating principles that can be discerned from, and applied to, all types of systems at all nesting levels in all fields of research" (Wikipedia, 2015). In other words, systems theory studies the structure and properties of systems in terms of relationships, from which new properties of wholes emerge. Systems theory, in its transdisciplinary role, brings together theoretical principles and concepts from ontology, philosophy of science, physics, biology, mathematics and engineering. Applications are found in numerous fields including geography, sociology, political science, organizational theory, management, psychotherapy, engineering and economics. This theory was established as a science by Ludwig von Bertalanffy, Anatol Rapoport, Kenneth E. Boulding, William Ross Ashby, Margaret Mead, Gregory Bateson and others in the 1950's. Among all the mentioned scientists’ share, Ludwig von Bertalanffy’s contribution, a Viennese professor of biology (1901-1972), was definitely the most influencing regarding the definition of system theory. He worked to identify structural, behavioral and developmental features common to particular classes of living organisms. One effective approach was to look over the empirical universe and pick out certain general phenomena, which are found in many different disciplines, and to seek to build up general theoretical models relevant to these phenomena, e.g., growth, homeostasis, evolution. The whole content of Bertalanffy's ideas was gathered into a General Systems Theory. Since he defined a general system as any theoretical system of interest to more than one discipline, his view could look at the world in terms of relationships and integration. In his scientific script systems are seen as integrated wholes whose properties cannot be reduced to those of smaller units. Instead of concentrating on basic building blocks or substances, the systems approach emphasizes the principles of organization. Every organism, from the smallest bacterium through the range of plant, animals and human beings - plus the family, society and the planet as whole - is an integrated whole and thus a living system. That is why an important aspect of systems is their intrinsically dynamic nature. Their forms are not rigid structures but they are flexible yet stable manifestations of underlying processes. System thinking is process thinking; form becomes associated with process, interrelation with interaction, and opposites are unified through oscillation. These oscillations are the ingredient that makes the development of systems unpredictable. Dynamical System Theory helps us dealing with this lack of predictability.

---

Fig. 1. A history map of the leading scholars and areas of research in complexity science.
Fig. 2. A visual, organizational map of complex systems broken into seven sub-groups.

Fig. 3. Graphical representations of some fields characterized by non-linear dynamics and complexity

Fig. 4. Earth’s circulation: an example of dynamic system.
"Dynamical systems theory is an area of mathematics used to describe the behavior of complex dynamical systems, usually by employing differential equations or difference equations. When differential equations are employed, the theory is called continuous dynamical systems. When difference equations are employed, the theory is called discrete dynamical systems. When the time variable runs over a set that is discrete over some intervals and continuous over other intervals or is any arbitrary time-set such as a cantor set - one gets dynamic equations on time scales. Some situations may also be modeled by mixed operators, such as differential difference equations" (Wikipedia, 2015).

What defined in mathematical terms can be now summarized in a less technical statement, subsequently referring to the aviation field. Focus of the dynamical system theory is not on finding precise solutions to the equations defining the dynamical system (which is often hopeless due to the nature of the equations themselves), but rather to answer questions like “will the system settle down to a steady state in the long term, and, if so, what are the possible steady states?” or “does the long-term behavior of the system depend on its initial condition?”. These questions are perfectly applicable to the main purposes aviation safety pursues in order to attain the 0-accident/incident condition. Usually, the aviation environment is identified with a dynamic system. In reality, aviation can be better related to a complex system. Differently from a pure dynamic system, the equations from which models of complex systems are developed derive from statistical physics, information theory, non-linear dynamics and represent organized but unpredictable behaviors of natural systems that are considered fundamentally complex. Complex system is also the name of the scientific field, which studies the common properties of systems considered complex in nature, society and science. Inherited from the mathematical analysis, the key problems of such systems are the difficulties with their formal modeling and simulation. From such perspective, in different research contexts complex systems are defined on the base of their different attributes. The study of complex systems is bringing new vitality to many areas of science where a more typical reductionist strategy has fallen short. Aviation is one of them. Only through the complete understanding of the non-linear behavior of accident/incident development aviation safety will be able to mitigate possible future mishaps. The recent implementation of risk assessment matrix by the aviation safety departments in their activity of examination and research shows how this unpredictability has lately become relevant for the aviation industry. Occurrences are classified in terms of probability and severity. This gives the management a cue about how much energy should be addressed to the different areas of the organization.

The evaluation of the severity of events is continuously updated by the technology advancements and by the improvements of modern devices to analyze the different threats, e.g. meteorology, structural engineering, aerodynamics, etc.

Two kinds of risk assessment matrix and an example of the likelihood scale definitions are shown.

---

**Fig. 5. Astrodynamics studies: an example of dynamic system.**

**Fig. 6. Risk matrix with numbers, letters and color codes.**

**Fig. 7. Risk matrix with color codes.**

**Fig. 8. Likelihood scale definition.**
The probability classification scheme shown in fig. 9 is extracted from ICAO Doc 9859 - Safety Management Manual. It specifies the probability as qualitative categories, but also includes numerical values for the probabilities associated with each category.

In fig. 10 we have an example of a risk classification matrix used in ATS that works in close connection with airline operations. Same as fig. 9, it has been extracted from ICAO Doc 9859 - Safety Management Manual. Severity is ranked as Catastrophic, Hazardous, Major or Minor, with a descriptor for each indicating the potential severity of consequences. Probability of occurrence is ranked through six different levels of qualitative definitions and descriptors are provided for each probability of occurrence.

### 2. Accident/Incident Curve

Through years, aviation safety investigations have identified the human factor as the primary source of mistake and, consequently, the primary cause of aircraft accidents/incidents. Observing the accidents curve along decades, we realize that it has a tendency towards “zero accident”, although it never reached that value. If we date back our analysis to the ‘60’s, we notice that the main reason of accidents/incidents was the “loss of aircraft control”. The origin of these kinds of event, “the loss of control”, was mainly associated with flawed human performances – such as distractions, fatigue, poor flying skills – with the contribution of defective ergonomics. Different ways to cope with these issues were implemented, first of all, technology. The introduction of the automation (auto-pilot, auto-throttle, flight director) represented the main relief for a fatigued pilot, though it lacked of automation, but to excess of it; or, to be more precise, the new phenomenon was linked not to a lack of automation, but to excess of it; or, to be more precise, the new phenomenon was linked not to a perfectly efficient aircraft crashing, while in control of pilots. Solutions to this threat were identified in two main areas: one technological, implementing the GPWS (Ground Proximity Warning System that lately became the EGPWS, Enhanced Ground Control Proximity System, see the end of this paragraph) and the other (more relevant) to train pilots to improve their ability to the teamwork. This problem arising from poor human interaction onboard was coped with via a psychological approach. Crews were trained to communicate effectively, to accept critics from colleagues, to develop better situation awareness, to support the teamwork and to improve their decision-making. A quick digression about the meaning of situation awareness and decision-making. Situation awareness is defined as the ability to detect, to understand and to anticipate what is going on. Decision-making is a systematic approach to the mental process used by pilots to consistently determine the best course of action in response to a given set of circumstances. All these aspects are associated to human behavior, not to technology.

Following the introduction of such courses to develop social competences, the accidents’ curve, once again, dropped. But, as in the never-ending co-adaptation between biological entities and viruses, or as in the continuous need for a satellite to adjust its motion correcting Space non-conservative perturbations, the solution was not long lasting. So, these countermeasures worked for about a decade, but eventually the percentage of accidents started to rise again. Investigators noticed the development of another dynamics, different from the ones experienced in the past. At the beginning of the ’90’s, the “loss of control” came back as main cause of aircraft crashes. It was very surprising, considered the technology introduced at all levels of the aviation system and the relevant costs of training of personnel that had produced an acceptable extent of reliability. The new phenomenon was linked not to a lack of automation, but to excess of it; or, to be more precise, to a badly designed automation. The constant introduction of new technologies onboard was driven by a philosophical change in the conception of safety. In fact, the engineering approach conceived the pilots as a threat in an otherwise flawless system. So, the most sensible solution was to replace the human contribution to a minimum, letting the computers with the adoption of the flight simulator during the training process. Simulation gave (and gives) the front-end operators the chance to become familiar with many possible scenarios, understanding the different behaviors of machines during abnormal and emergency operations.

So, with the human factors representing a threat to the aviation safety, technology provided the right answer to lower the accidents/incidents curve. This approach worked fine until the mid-’70’s. In 1975, the conference held by IATA (International Airlines Transport Association) in Istanbul pointed out as the human factors should be thoroughly investigated to obtain a better reliability in the Civil Aviation domain. In fact, the analysis of some occurrences highlighted a new dynamics leading to accidents. Investigators were puzzled by the fact that the main cause of accident shifted to the so-called Controlled Flight into Terrain (CFIT). This kind of accidents is generally characterized by a perfectly efficient aircraft crashing, while in control of pilots. Solutions to this threat were identified in two main areas: one technological, implementing the GPWS (Ground Proximity Warning System that lately became the EGPWS, Enhanced Ground Control Proximity System, see the end of this paragraph) and the other (more relevant) to train pilots to improve their ability to the teamwork. This problem arising from poor human interaction onboard was coped with via a psychological approach. Crews were trained to communicate effectively, to accept critics from colleagues, to develop better situation awareness, to support the teamwork and to improve their decision-making. A quick digression about the meaning of situation awareness and decision-making. Situation awareness is defined as the ability to detect, to understand and to anticipate what is going on. Decision-making is a systematic approach to the mental process used by pilots to consistently determine the best course of action in response to a given set of circumstances. All these aspects are associated to human behavior, not to technology.
onboard do the job. Consequently, some jobs - as the flight engineer, whose main task was to monitor and manage the aircraft systems - disappeared. There were other unintended consequences of this approach. For example, new-hired pilots were no more requested to demonstrate such a high level of flying skills as in the past. More and more technology lowered the workload, wearing away even the acquired flying competences. It led, moreover, to a double and somehow contradictory pilot behavior: complacency on one side and automation surprise on the other. It means that with complacency induced by the over-redundancy provided by the automation onboard, the basic flying skills were eroded and the situation awareness narrowed. On the other hand, the pilot’s knowledge dried-up as a result of the systems opacity, inducing the “automation surprise” in the final operator, unaccustomed to manage the failure of automatic flight functions.

So, we are now at a turning point, again. During the ‘80’s the engineering approach wondered if the human contribution onboard was a threat or resource. Now, conversely, we ought to ask ourselves: is automation a threat or a resource? In the above-illustrated accidents brief history, we notice a shift in their causes, following the countermeasures taken by the aviation community to deal with rising threats. As we have shown, all the different solutions adopted to keep the accidents rate under control eventually led to some new menaces.

**Insights**

ILS, the Instrument Landing System, is a precision approach radio aid that gives slope and track guidance to enable low-minima approaches for suitably equipped aircraft. An ILS has two separate ground transmitters: the localizer and the glideslope. The former provides tracking guidance along the extended runway centerline, e.g. azimuth guidance left and right of the extended runway centerline. The latter gives vertical guidance toward the runway touchdown point, e.g. vertical guidance above and below a virtual path. The glideslope is normally set at an angle of 3 degrees to give a reasonable rate of descent. The aircraft needs its own ILS receiver to pick the electromagnetic signals, decipher the information contained in them and display it on the onboard flight instruments. The ILS localizer works in the 108-112 MHz VHF bands, which it shares with the VOR (another navigation device). To avoid confusion with VOR signals, the ILS uses frequencies at odd 100- and 150-kHz spacing. The glideslope frequency is selected automatically when its paired VHF localizer channel is selected. Distance-measuring equipment (DME) is usually coupled with the ILS frequency and automatically selected with the ILS too. DME is a form of secondary radar that outputs continuous distance readout, in nautical miles, of the slant range to a ground station. It operates in the ultrahigh frequency (UHF) band, between the 962 and 1213 MHz, and uses transmissions with line-of-sight propagation paths. Marker beacons are particular types of VHF radio beacon that emits pulses of dots and lines (morse code), which represents some defined positions along the ILS beam.

The GPWS is a central computer system that receives various data inputs on configuration, height/altitude and instrument landing system (ILS) glideslope deviations (vertical deviations). It calculates these inputs to detect if any of the following dangerous or potentially dangerous circumstances exist: excessive rate of descent, excessive terrain closure rate, height loss after takeoff, flaps or gear not selected for landing, too low flight path compare to the glideslope signal, descending below minimum altitude of obstacles in short final approach toward the runway. These circumstances form the six main working modes of the GPWS. Each mode has a pre-programmed active range with distinct boundaries of alerting. Most modes have two boundaries: an initial caution one related to potential danger and a warning one, where this danger to the safety of the aircraft exists. If the central computer detects that any boundary has been exceeded, it will activate aural and visual warning to the flight crew.

EGPWS, the Enhanced Ground Proximity Warning System, provides a greater level of detection than a standard GPWS. Terrain displays, windshear hazards are some of the new features adopted on this more advanced system, suitable for use only on aircraft with digital avionics.

### 3. Safety

“Safety is the lubricating fluid that gives the complex machine of transportation the chance to work and evolve”. We started with this preliminary definition of safety, but, going deeper to a general explanation of the term, we find “Safety is the state of being ‘safe’, the condition of being protected against physical, social, spiritual, financial, political, emotional, occupational, psychological, educational or other types or consequences of failure, damage, error, accidents, harm or any other event which could be considered non-desirable. Safety can also be defined to be the control of recognized hazards to achieve an acceptable level of risk. This can take the form of being protected from the event or from exposure to something that causes health or economical losses. It can include protection of people or of possessions” (Wikipedia, 2015). Aviation safety definitely goes beyond this. We can use the same source, Wikipedia, to start outlining what air safety is. “Aviation safety is a term encompassing the theory, investigation, and categorization of flight failures, and the prevention of such failures through regulation, education, and training. It can also be applied in the context of campaigns that inform the public as to the safety of air travel”. Safety in aviation is not only a perception or an active action (e.g. fatalities prevention). It is the heart of the aviation organizations, what leads the development of every procedure performed by the company operators. Safety relates to a proactive attitude toward the verification of any incident or accident, “focusing on dynamic training programs and the spread of safety culture” (Chialastri, 2011). For example, every year flight crew training syllabi change at least two or three times, adjusted by many factors, such as the introduction of new technologies or the mitigation of some future errors (e.g. after a negative event that clearly underlined a crew or a system deficiency). So, no more reactive approach, but a proactive one, in other words a shift from “recovery after a
mishap” to “avoidance of new ones”. The former takes place when, after an unexpected event, the organization uses all its resources to react to the accidents effects, hoping it will not happen again. This dynamics is driven by “the blood priority”, meaning that any countermeasure is taken exclusively after fatalities and/or damages to the system occur, even if many warnings showed up before the occurrence. Indeed, using the proactive safety, the organization sets a series of actions to forestall the adversities, planning financial resources and, as stated before, developing the culture of safety in the entire staff involved in the operations.

In summary, throughout the history of aviation, safety evolved from a mere post-incident/accident investigation department to a complex system, as known as SMS, Safety Management System. Company SMSs are nowadays so important for airlines, that they have a special place in the organization chart and their managers are often members of the board of directors. Modern SMSs also include the Quality System, previously separated in a different department.

The way safety contributes to the health of an aviation organization is based on the most advanced theories dealing with dynamic systems (e.g. the risk assessment matrix we illustrated in the introduction). The resilience engineering is the most common complex approach used in aviation today.

4. Resilience Engineering

The change of accidents causes through the last sixty years pushed the aviation industry to develop several means and theorize complex approaches to mitigate the happenings of possible detrimental events. Aviation organizations such as air transport companies, flying schools, military departments, universities, strove to find out new ways of preventing incidents and accidents.

The change of conception from reactive to proactive attitudes toward incidents/accidents is historically connected to the evolution of another kind of approach to safety, which can be divided in two main areas: the approach to the individual and the systemic approach. The first believes that the incidents and accidents happen because the front-line operator does not follow the standard when he/she accomplishes his/her tasks. So, the only way to avoid of any danger is to apply punishments or even to get rid of these personnel. On the other side, the systemic approach tries to identify the main reasons that induce the staff to make mistakes inside the organization. Let’s see shortly the main difference between these two theories.

In the individual approach, to err is not allowed, so there is a research to find a scapegoat for every mishap, the failure depends from a faulty action made by a liable person. In this way, mistakes tend to be covered-up, everyone keeps relevant information about safety for him/herself and inevitably an accident comes “out of the blue”.

In the systemic approach, organizations are aware that to err is human. Thus, they try to limit the scope and the severity of errors via a thorough analysis of incidents/accidents, disseminating all the useful information about threats and implementing departments and areas entirely dedicated to safety with the task to monitor even minor events. In this safety conception, the human contribution is essential and represents the main resource to ensure a high safety level.

So, the human judgment remains the last barrier against accidents, the sole “device” that is able to adapt the rule to the operation in progress or even to deviate from it, having deemed the adaption and the deviation safer than the blind execution of the standard task (e.g. the mentioned continuous adjustment to the unpredictability of complex systems). At the moment, machines lack this sound judgment.

Resilience Engineering is a new complex way to approaching safety and it is based on the following paradigm: air crashes and fatalities occur out of the same reasons why flight operations successfully guarantee a good level of safety (see the brief case study following the paragraph about automation for further explanation). Erik Hollnagel underlines the importance of weak signals emerging from the daily activities to better understand how to improve all the safety levels in high complexity organization (Hollnagel et al., 2006).

As we explained in the introduction, the main feature of complex systems is their dynamic stability/instability equilibrium; in short, you must move to be balanced. Resilience is what makes these systems robust and, at the same time, flexible. In Physics, and especially in the Science of Materials, it is the ability of an object to absorb the external perturbations, keeping its internal organization/characteristics unvaried; this is due to the property of the structure to absorb energy when it gets elastically deformed and to release this energy upon unloading. The maximum energy the object can absorb without creating a permanent distortion is the modulus of resilience.
A good behavior in aviation comes from a base of mental/physical health on which technical/non-technical skills and positive attitude are built. For aeronauts these are the minimum items they have to "carry" everyday at work in order to safely operate in heterogeneous crew and proactively prevents incidents/accidents. This shows how a resilient system has far deeper roots compared to what everyone of us can think. Every crewmember’s routine can influence the outcome of flight operations and the future of the resilient system.

The same principle applies at the organizational level. To safeguard the succession of every phase of flight, robustness and flexibility can be accomplished only with the use of professional judgment, adjusting the inputs for the actual conditions and coping with the unexpected. In the event of any irregularities, the organization, like a physical object, will be ready to “receive the stress of bad circumstances” and to react elastically avoiding most of the catastrophic consequences. The capability of the organization to create adequate risk models and to correctly use the resources in a proactive manner, creating a good synergy, is what makes Resilience Engineering able to face any disturbing input to the normal operations and properly manage the economical resources. According to the main thought of Resilience Engineering, incidents and accidents do not come from system flaws or individual mistakes, but from the lack of ability of the complex system to adapt its framework to the changed complex environment (Chialastri, 2011).

We now define automation before analyzing the relationship between safety and automation philosophy.

---

**Fig. 13.** Elements of a basic resilient system. A good behavior in aviation comes from a base of mental/physical health on which technical/non-technical skills and positive attitude are built. For aeronauts these are the minimum items they have to "carry" everyday at work in order to safely operate in heterogeneous crew and proactively prevents incidents/accidents. This shows how a resilient system has far deeper roots compared to what everyone of us can think. Every crewmember’s routine can influence the outcome of flight operations and the future of the resilient system.

**Fig. 14.** Resilient can ride the risk!!

**Fig. 15.** An example of a resilient system: the system actuates a continuous flow of info to enhance the quality of the output.
5. Automation

Consistent with a shared definition, automation may be defined in the following way: “Automation is the use of control systems and information technologies to reduce the need for human work in the production of goods and services”. Another plausible definition, well-suited to the aviation domain, could be: “The technique of controlling an apparatus, a process or a system by means of electronic and/or mechanical devices that replace the human organism in the sensing, decision-making and deliberate output” (Webster, 1981).

The Oxford English Dictionary (1989) defines automation as:

1. Automatic control of the manufacture of a product through a number of successive stages;
2. The application of automatic control to any branch of industry or science;
3. By extension, the use of electronic or mechanical devices to replace human labor.

According to Parasumaran and Sheridan, automation can be applied to four classes of functions:

1. Information acquisition;
2. Information analysis;
3. Decision and action selection;
4. Action implementation.

Information acquisition is related to the sensing and registration of input data. These operations are equivalent to the first human information processing stage, supporting human sensory processes. If we adopt a decision-making model based on perception, identification, mental process, decision, action, follow-up and feedback, we may see the element of information acquisition to be likened to the first step: perception. Let’s imagine a video camera and the aid it offers in monitoring activity. It helps to replace continuous, boring, monotonous human observation with reliable, objective and detailed data on the environment. Automation may accomplish these functions better than humans, in a more efficient way to detect objects. In fact, it offers the possibility of positioning and orienting the sensory receptors, sensory processing, initial data pre-processing prior to full perception, and selective attention (e.g.: the focus function in a camera).

Information analysis is related to cognitive functions such as working memory and inferential processes. It involves conscious perception and manipulation of processed items. It allows for quick retrieval of information in the working memory. In aviation, this kind of system is broadly used to provide pilots with predictive information, such as how much fuel will be available at destination, where the top of climb or top of descent is located in order to optimize the flight path, and so forth.

With regard to decision and action selection, automation is useful because it involves varying levels of augmentation or replacement of human decision-making with machine decision-making. It is generally acknowledged that human decision-making processes are subject to several flaws, among them a tendency to avoid algorithmic thought, a biased development of pros and cons based on the laws of logic, a partial view of the overall system and, often, a biased judgment because of the heavy influence of emotions.

The fourth stage involves the implementation of a response or action consistent with the taken decision. Generally, this stage of automation replaces human hands or voice. Certain features in the cockpit allow automation to act as a substitute for pilots. For instance, this occurs when – following an alert and warning for windshear conditions – the automation system detects an imminent danger from a power setting beyond a pre-set threshold. In this case, the autopilot automatically performs a go-around procedure, which avoids a further decline of the aircraft performance.

Besides being applicable to these functions, automation has different levels corresponding to different uses and interactions with technology, enabling the operator to choose the optimum level to be implemented based on the operational context (Parasumaran, Sheridan, 2000). These levels are:

1. The computer offers no assistance; the human operator must perform all the tasks;
2. The computer suggests alternative ways of performing the task;
3. The computer selects one way to perform the task and
   a. Executes that suggestion if the human operator approves, or
   b. Allows the human operator a limited time to veto before automatic execution, or
   c. Executes the suggestion automatically then necessarily informs the human operator, or
   d. Executes the suggestion automatically then informs the human operator only if asked, or
   e. Chooses the method, executes the task and ignores the human operator.

This last level is gradually becoming the most used in a flight deck and the tendency is that soon human sound judgment will be substituted by a synthetic task accomplishment. So, the only barrier to prevent incidents and accidents will be excluded from the chain of the onboard procedures. We can give an interesting example of it, referring to the LOC-I prevention. We know the loss of control inflight is the major cause of accident today. After several cases, especially those happened between 2009 and 2014 (e.g. Air France AF447 in 2009, Asiana Airlines OZ214 in 2013, AirAsia QZ8501 in 2014), the aviation community decided to review the training syllabi of the crews. The initial proposal saw pilots undergoing some basic trainings regarding unusual attitudes and stall prevention/control every six month. The cost of this was a big economical commitment by the airlines that immediately obtained by the authorities the chance to extend this requirement to one year. Not so far from now it will be probably reduced to once every three semesters. The reason? One more time, the
inclination to extreme automation seems to be taking place and aiming to override the human intervention. For example, some tremendously innovative projects about neuroergonomics are under final review and possible future approval. They will introduce an avatar pop-up on the flight deck monitors in order to suggest pilots the action to be performed. In details, this avatar pop-us will trigger the crew’s attention on the missing task, displaying a color-activated picture that simulates the missed accomplishment. The short video loop will activate human mirrors neurons, which tend to direct the person to imitate what his/her eyes are seeing. In this way the final operators will be assisted during high workload in an emergency, when the brain’s aural channel is the first to be shut down. (AIN International, April 2015). But, it looks these researches will not be limited to simple duties. Many successful trials are quickly pushing the aeronautical industry to hardly work on them. There are daily rumors from some manufacturers stating that this technology will be implemented and installed on the next production of airplanes, which will start to fly no later than 2020. On the Aviation experts’ point of view this will be a great leap in front-end operators’ assistance during critical flight phases, as well as a huge threat if not properly used. Training will be anyway needed to get confident to the new technology and the most beneficial way to get advantages will be to not abuse with massive introduction of pop-ups. A good way to mitigate the sparks of possible future accidents will be the participation of final operators, such as flight crew and maintenance, to the early stages of this technology development. Crew’s decision-making has to remain the leading method of safe flight operations conduction.

5.1. Brief Case Study

In a report released on the 1st of December 2015 the Indonesia National Transportation Safety Committee (INSC) concluded the accident investigation stating that a faulty rudder-control components and pilots’ response to the problem contributed to the crash of AirAsia Indonesia Flight QZ8501 in December 2014. The Airbus A320 crashed in the Java Sea after departing from Surabaya, Indonesia, on a flight to Singapore, with the loss of 162 passengers and crews. INSC investigators detailed the sequence of the events that led to the fatality. A cracked solder joint that resulted in a loss of electrical continuity and the failure of rudder travel limiter units (RTLUs), which restrict the rudder deflection angle of the vertical stabilizer, were identified as the main technical failures of the flight. However, the aircraft maintenance records showed that there had been 23 RTLUs problems over the course of 2014.

To better introduce the main automation concepts related to this case study, let’s summarize the events of the last minutes before the mishap. Once the aircraft reached cruising altitude, the flight-data recorder (FDR) indicated there were four master caution alerts associated with the RTLUs over 14 minutes. Following the fourth alert, pilot actions triggered two more master cautions reporting faults with the flight augmentation computer that manages rudder control functions. The FDR indicated that the circuit breaker to the computer was reset, resulting in an electrical interruption. After the sixth master caution, the autopilot and auto-thrust disengaged, and the flight-control logic of the aircraft’s fly-by-wire system reverted from normal to alternate operation. “Subsequent flight crew action leading to inability to control the aircraft in the alternate law resulted in the aircraft departing from the normal flight envelope and entering prolonged stall condition that was beyond the capability of the flight crew to recover,” a part of the report states. Among safety recommendations, the committee called on Airbus to develop a means for pilots “to effectively manage multiple and repetitive master caution alarms to reduce distraction”.

This is a typical example of how an aviation organization can fail to adopt a proactive attitude toward the possibility of an accident. The final events are just the top of an iceberg representing multiple latent factors that, underwater, interact together in a random way, leading the events to the disaster. These small latent elements can be described in two ways: one following human factors principle and the other one modeling them as elements of a complex system (using what we learned in the introduction about dynamic systems and von Bertalanffy’s General System Theory).

In an optic of human factor/CRM (see end of this paragraph) concepts latent items have a double role. They are the same features that guarantee safety as well as threaten it (Hollnagel, 2006; Resilience Engineering basic element). We can use an example to make this apparently awkward combination clear. Standard procedures for flight operations cannot cover all cases; we often underlined that aviation is modeled as a complex system. So, during a routine sector pilots will execute tasks, continuously adapting them to the actual flying conditions. Sometimes they will use local adjustments to safeguard the good progress of the operations. Delaying or anticipating some procedure applications, using correct margins are just few of the multiple deviations from the standard guide a pilot has to “daily” apply. Unfortunately, today crewmembers have to be much more careful adding flexibility to their job. Neglecting the responsibility maintenance has in the accident, we can use this AirAsia’s event to clearly state that nowadays the use of smart shortcuts can be fatal. One more time, without a thorough knowledge of automation, deselecting certain devices in order to take full control of the transportation mean is no more possible. The possible consequential change of the control law of the aircraft will most likely lead the flight conditions to an uncontrollable state. This concept can be emphasized giving the other mentioned description of latent elements, a mathematical/system theory oriented one. To do this, we have to connect the unexpected random itinerary of the system latent factors to those oscillations we studied in the introduction, again outlining Ludwig von Bertalanffy’s theory. We reported: “In his scientific script systems are seen as integrated wholes whose properties cannot be reduced to those of smaller units. Instead of concentrating on basic
building blocks or substances, the systems approach emphasizes the principles of organization. Every organism, from the smallest bacterium through the range of plant, animals and human beings - plus the family, society and the planet as whole - is an integrated whole and thus a living system. That's why an important aspect of systems is their intrinsically dynamic nature. Their forms are not rigid structures but they are flexible yet stable manifestations of underlying processes. System thinking is process thinking; form becomes associated with process, interrelation with interaction, and opposites are unified through oscillation”.

Now, as we did for the CRM point of view, we can associate human actions to latent failures, in their double nature, beneficial and harmful. Carefully looking at the latent failures we can model them as elements of a complex system. Using a further approximation, we can extend this concept including the binomial human-machine and easily recognize it as a structure of the aviation environment in its variability and unpredictability: “…instead of concentrating on basic building blocks or substances, the systems approach emphasizes the principles of organization...deliberate omission…aspect of…their intrinsically dynamic nature”. As we stated in the introduction, the equations used in the complex system theory are characterized by non-linearity, making them not solvable, unless certain conditions are added to the beginning of the resolution. Theory and reality both give the idea of how critical is to deal with items in continuous evolution. Sometimes boundary conditions cannot be easily defined and the subsequent management of these dynamic elements needs a non-stop update. Fortunately, mathematically speaking, today we have powerful machines, able to face all these changes through fast calculation capacities.

This is the reason why today human-machine interaction is so important. It represents a future challenge for aviation organizations. Investments of resources in training courses for crew to better understand what lies behind few flat screens of the flight deck will be the key factor to cope with latent factors path. Using a magnifying glass, let’s explain in a more detailed way how we can safely move in this complicated habitat.

5.2. Insights

CRM - Crew resource management or cockpit resource management is a set of training procedures for use in environments where human error can have devastating effects. Used primarily for improving air safety, CRM focuses on interpersonal communication, leadership, and decision making in the cockpit. Crew resource management formally began with a National Transportation Safety Board (NTSB) recommendation made during their investigation of the United Airlines Flight 173 crash. There a DC-8 crew ran out of fuel over Portland, Oregon while troubleshooting a landing gear problem. The term "cockpit resource management" (later generalized to "crew resource management") was coined in 1979 by NASA psychologist John Lauber who had studied communication processes in cockpits for several years. While retaining a command hierarchy, the concept was intended to foster a less authoritarian cockpit culture, where co-pilots were encouraged to question captains if they observed them making mistakes. Crew Resource management grew out of the 1977 Tenerife airport disaster, where two Boeing 747 aircraft collided on the runway killing 577 people. A few weeks later, NASA held a workshop on the topic, endorsing this innovative training. United Airlines was the first airline to provide CRM training for its cockpit crews in 1981. By the 1990s, it had become a global standard. United Airlines additionally trained their flight attendants to use CRM in conjunction with the pilots to provide another layer of enhanced communication and teamwork. Studies have shown that by both work groups using CRM together, communication barriers are reduced and problems can be solved more efficiently, leading to increased safety. CRM training concepts have been modified for application to a wide range of activities where people must make dangerous time-critical decisions. These arenas include air traffic control, ship handling, firefighting, and medical operating rooms. (Wikipedia, 2015)

6. Human-Machine Interaction

As often highlighted in this paper, since the ’90’s the main cause of aircraft accidents has been identified in the “loss of control”.

This is the starting point of human-machine interaction analysis in the present paragraph.

Let’s begin saying that the evolution of the human being, through its almost 40000 years of Homo Sapiens’ existence, saw a normal healthy human body interacting with a two-dimension reality (up-down, left-right). In less than a hundred years the human being learned to fly, coping with and fitting to the third dimensions. Today a front-line operator has to continuously adjust the inputs coming from all his/her sensory systems, which use multiple decoding made by an “ancient” brain.

In fact, though we live in a three-dimensional World, the processes of images depth evaluation in flight, caught by the eye structure, are impressed in a bi-dimensional way on the retina. Modifying the biological shape of the crystalline, widening the pupil, changing the convergence of the eye, and so on, a human can estimate the depth and proportions of objects around, integrating this information with habit inputs to have a more pertinent reality-related data (Chialastri, 2012a). Normally, human visual habits are developed during the first years of youth formation and education, a long time before a flight crewmember gets his/her licenses. Once airborne, these natural visual aids are missing. Aviation environment makes difficult for a pilot to deal with all these adjustments and accomplish his/her flight tasks. The solution to it lies in the so-called Human Factors, which assist the pilot in his/her adaptation to unfriendly environments. Human factors, in the modern meaning, is that branch of science that searches the best way to:
• Build user-friendly environments, where operators have to work;
• Modify tools that operators have to manipulate in order to carry out correct assignments.

In the Anglo-Saxon acceptance human factors is a synonym of Ergonomics.

On the other side, the machines evolution - apart from some former autopilot systems - started immediately in a tridimensional context. System designs (ergonomics) rapidly improved, permitting rapid and precise execution of automatic tasks to lower the operator’s workload. The enhancement of pilots’ performances was largely due to the introduction of automation onboard.

On modern aircrafts the human-machine interaction is continuously and rapidly changing. The fast growth of technological application in our everyday life and especially in aviation is modifying the habits and subsequently the skills of front-line operators. The last generation of aircraft demonstrates that an aircraft could be flown without any human intervention (or with a minimum of it, e.g. the mentioned “avatar pop-up” in the paragraph about automation). In the last twenty years we experienced a quick transformation in the aircraft building philosophy. Once, to study the electrical system of an airplane, a pilot was put on training for a week. Now, in a couple of hours, the electrical system is shown to him/her. It means that the thorough knowledge, available to the pilot, has been replaced with a shallow awareness of what is behind the pilot’s panel.

We can thus define the shift from an epistemological airplane (strategic) to the methodological one (tactical). As we have told, knowledge is a big resource in a complex system, like aviation. If we consider the resilience as the faculty to respond to the unexpected, this faculty arises from a deep knowledge of the system. With the latest innovation in the airplanes philosophy, this knowledge has been greatly eroded.

According to the Anthony’s Pyramid (Anthony, 2010), we notice that the strategy, at the decision-making level, is on the top and corresponds to the action of “lead”, while tactics is related to the “control” phase.

Fig. 16. Two common representations of the Anthony’s Pyramid. It can be seen as the pyramid of safe operations, where more complex tasks are assigned to the top in terms of less people able to conduct them, less available resources and less margin for mistakes. In modern aviation there is the tendency to leave the lead level to automation and limit the human being’s tasks to a mere control.

Modern planes are all controlled through strict procedures and often pilots don’t know what lies behind the interface. The result is: safe operations shape is no more a pyramid and the decision-making level lies under the basic control of what automation does.

“We created machines that we are not able to drive”, Professor Fabrizio Bracco says in his “Promuovere la sicurezza” (“How to promote safety”, 2013), and he continues “…human beings were able to build very complex and advanced systems, but at certain stage unable to control them in an efficient fashion…”

And so we may say that in the traditional airplane, pilots had in mind the entire process activated with a cockpit switch: reservoir, manifolds, filters, pumps, actuators, and so on. He/she knew in which part of the system the failure was located. In a word, he/she activated a known system.

Today, with the introduction of fly-b-y-wire concept, glass cockpit design, and considered the opacity of the interaction behind the cockpit switches, levers and buttons, the pilot merely knows the procedure that conducts to a desired result, but not what is behind the panel. In fact, every switch gives input to a series of computers, which, according to the airplane speed, flight phase, configuration and others parameters, manages the flight progress, activating or de-activating the needed commands. We may say that pilots operate an opaque ecosystem of which they are partially unaware.

The complex and fast interactions in the “jungle” of different computers don’t give the pilot the chance to follow step by step the process of information acquisition, analysis, decision and so on.

If we look at the scheme of a common system in the operation manual of these modern aircrafts (commonly known as AOM – Airplane Operating Manual, AFM – Airplane Flight Manual) when we focus on the system description, we can notice an over-simplification of aircraft systems. In fact, if we come across them at the maintenance or manufacturer’s level, we notice that there many more data and details.

Even though pilots do not need to know too many engineering notions, it is important to underline that some of them, concerning Fundamental of Automatics and Electronics, could be beneficial to better understand how to deal with the aforementioned “electronic ecosystem”. For instance, a common Airplane Operating Manual/Aircraft Flight Manual scheme represents an autopilot or a flight director connection with just a line to show that they are somehow linked.
Indeed, the project engineer and manufacturer manual point out several useful symbols to the comprehension of the process ongoing. Their system descriptions, lately in a pure digital format, are organized in complex schemes and layouts.

Fig. 17. Airplane Operating Manual (Aircraft Flight Manual scheme for pilots).

Fig. 18. Schemes and layouts for project engineers.
Fig. 19. Schemes and layouts for flight test engineers. Inputs and outputs are logically connected and in some cases, e.g. on the right side of the figure (in Italian), physics concepts related to characteristic equations are added.

Fig. 20. Scheme and layouts for maintenance, usually for long maintenance checks, usually called “heavy maintenance”. Those used for transit maintenance are more simple, sometimes just algorithmic stepped procedures.

Fig. 21. Programming language tool used in CATIA III.
One of the programming language tool used is CATIA (for the definition, see end of this paragraph). Just a fast glance to any of its system plots immediately suggests the need of a detailed legend only to understand the basics. To go deeper and be familiar with the full outline requires specific courses.

Another useful notions for pilots would be those related to Control Engineering. Understanding a common Simulink framework (for the definition, see end of this paragraph) would give crew the chance to see:

- System lags of action/reaction (time between the trigger of a command and the execution of the required action according to how the information are processed by the ecosystem of computers);
- System saturation of commands (the limits that the system has at different operating levels: normal, abnormal, emergency situations);
- System damping modes, used to avoid any sharp variation in the received inputs from sensors. For example: the activation of some weather radar working improvement out of adverse external conditions.

Fig. 22. Samples of simulink schemes and matlab files (they are not related to each other). Quality of the picture is not important here. What counts is to show how more complex are these concepts of control engineering compared to the simple design given to final operators. Getting used to the logic of these control engineering tools would possibly give future pilots the chance to better understand automation.

So, while in the past decades the awareness of physical items locations inside of the aircraft and their way of working was a “need-to-know” for pilots, for the upcoming years a big change in pilots’ tuition will be required. Future pilots will have to be able to interact with systems through pure automation. Their license subjects will not be focused on how the flight controls, flight guidance, electrical, air-conditioning systems, autoland work, but on how the aircraft automation manages them. This will give crews the ability to “fly ahead the airplane”, common term used by instructors to teach their students during various phases of training (e.g. new-hire, upgrades). Final operators will be able to fully communicate with the onboard ecosystem, using the same language technology uses, but this will be possible only:

- drastically updating the training syllabi for currently flying pilots;
- deeply reviewing the instruction platforms for future aviators.

Regarding these two important focal points we identify two possible paths to be followed about forthcoming teaching in aviation. The former deals with the actual generation of aircrafts and the handling of abnormal or emergency procedures onboard. Referring to what we said about automation, the simple reading of any checklist
Developed by Math Works, MATLAB allows matrix for multi-domain simulation and Model-Based Design. Simulink, developed by Math Works, is a data flow graphical programming language tool for modeling, simulating and analyzing multi-domain dynamic systems. Its graphical programming language tool for modeling, simulating and analyzing multi-domain dynamic systems. Its implementation of algorithms, creation of user interfaces, manipulating, plotting of functions and data, and interfacing with programs written in other languages, including C, C++, Java, and Fortran (Wikipedia, 2015).

MATLAB (matrix laboratory) is a numerical computing environment and fourth-generation programming language. Developed by Math Works, MATLAB allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages, including C, C++, Java, and Fortran (Wikipedia, 2015).

### Definitions:

**CATIA** (Computer Aided Three-dimensional Interactive Application) is a multi-platform CAD/CAM/CAE commercial software suite developed by the French company Dassault Systèmes directed by Bernard Charlès. Written in the C++ programming language, CATIA is the cornerstone of the Dassault Systèmes software suite (Wikipedia, 2015).

**Simulink**, developed by Math Works, is a data flow graphical programming language tool for modeling, simulating and analyzing multi-domain dynamic systems. Its primary interface is a graphical block diagramming tool and a customizable set of block libraries. It offers tight integration with the rest of the MATLAB environment and can either drive MATLAB or be scripted from it. Simulink is widely used in control theory and digital signal processing for multi-domain simulation and Model-Based Design.

**MATLAB** (matrix laboratory) is a numerical computing environment and fourth-generation programming language. Developed by Math Works, MATLAB allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages, including C, C++, Java, and Fortran (Wikipedia, 2015).

### 7. Conclusion

All the covered scientific subjects and all the considerations about possible safety improvements have been discussed to constantly underline that, only preserving safe operations, efficient mobility will lead to the economic prosperity and sustainable living.

Aim of this paper was to show the connection between aviation safety and automation philosophy, focusing on human-machine interaction.

Let’s quickly recap. We quoted that, during the ‘90s, the “loss of control” became the main source of accidents so far. Poor human-machine interaction is one of the driving forces behind those events, so it is nowadays necessary to continuously analyze why humans interact so badly with new devices.

My opinion is that a better design at the early stage of new projects, involving the final operator in the developing teams, could greatly diminish the impact of automation in causing accidents. The problem we must set is: “Where does human get the reserve, the redundancies to cope with the system oscillations, when we talk about automation?” In the past, thorough knowledge was one of the main resources to adapt the pilot’s behavior to an ever-changing environment. He/she could easily invent new solutions, deviate from procedures; manage unexpected situations with his/her airmanship, defined as the synthesis of the ability, experience and familiarity accumulated on the job. As we discussed, these concepts are hardly applicable today, because of the excessive level of automation introduced onboard. I also theorized some other solutions to mitigate this concern and delineated two possible paths about crew trainings.

A new role of “pilots as flight operations managers” will be the key issue for the safety seekers.

I would like to end up this paper with a message to the experts and operators working at other dynamic systems, as those mentioned at the beginning of this paper. Surface and marine transportations often follow aviation in the improvements regarding safety, as well as aviation often inherits technology innovations from space flying and exploration. It would be extremely beneficial to build a more active interdisciplinary collaboration at different levels of competency. Sectors like medicine, aviation, air traffic control, fire departments in a growing number countries are already tracking common ways to best navigate in complex areas of dynamic systems.

Our wish is to involve the maximum number of industrial divisions.

Differences make wealth.

### References

Interface – A Human-centered design approach


Boeing website, www.boeing.com


Chialastri Antonio (2012a), Human Factor – Prestazioni e limitazioni umane, IBN editore, Roma.


Curtis Howard, (2010), Orbital Mechanics for Engineering Students, Elsevier Lid, Burlington, MA, USA.

De Maria Gerardo (2014), Conference “Automation in Aviation”, University La Sapienza, Rome, Italy.


