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The long journey toward a higher level of automation in ATM as safety critical, sociotechnical and multi-Agent system

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Abstract

The main objective of this paper is to present our vision of the role of automation in future air traffic management (ATM) system. It also includes an analysis and state of the art on ATM and automation. The content is based on HALA! position paper, that looks beyond the framework defined by SESAR and NextGen for the near future, and analyses the feasibility of higher levels of automation in ATM in the far future, taking into account the relationship between humans, organizations, and machines and scoping the allocation of functions, roles, and tasks between them.

Taking into consideration the proposed SESAR&NextGen paradigm shift (trajectory-based operations; proactive, more distributed and autonomous system) and studies developed in ATM automation in the past years, the vision goes toward a more ATM automation system operation questioning even the possibility of fully automated ATM system. The understanding of higher levels of automation in ATM considers the "overall system performance" as main driver for the resulting "optimal" ATM level of automation.

Implementation of above programs will change the human role in the future ATM system. In this regard, the vision considers ATM as sociotechnical system and orchestrated organization, overcoming the former consequences of automation, where some "human errors" caused from automation were found, to this new vision where human motivation for their engagement in the ATM activities, will be promoted.

New roles between humans, organizations, and between them and machines will be derived by considering ATM as a complex sociotechnical multi-agent system. Under this assumption, it will be essential: to maintain a high degree of autonomy among different ATM agents and, simultaneously, an optimized level of orchestration among them.

Three interdependent criteria to support the always controversial decision about where to dynamically allocate the ATM essential functions/tasks are proposed;

- when is the "best time" to take an operational action,
- where is the "best place" having the best picture to take it and, finally,
- who will be the "best player" to implement the associated tasks.

As a result, the paper advocates for a different role of automation devoted to support a temporal, institutional, and physical distributed ATM system.

It is also pointed out that research in ATM automation should always take under consideration the adequate level of automation in the far future ATM system and should always ensure the safety and reliability of a highly automated ATM system.

Finally considers the need to align the research efforts into two different main activities of improvement, devoted to: aircraft trajectory hierarchal, spatial, and temporal cohesion and trajectory management.

Keywords

ATM, trajectory-based operations, automation, human system integration, ATC, multi-agent, orchestration, complexity

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ATM, what is today and what should be tomorrow

Air traffic management (ATM) encompasses all airborne and ground-based functions and services required to ensure the safe and efficient movement of all airspace users. Current ATM approach is

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mainly ground based and composed of three major functions:[1–3]

1. Air traffic services (ATS): aimed to provide and ensure all tactical activities supporting safety and efficiency of air traffic during all flight, including Air Traffic Control (ATC), flight information service (FIS), and alerting services (ALSs).
2. Air traffic flow and capacity management (ATFCM): aimed to ensure an adequate flow of air traffic through airspace, respecting all air traffic flow limits such as ATC sector capacity, ATC, and airport capacity constraints.
3. Airspace Management (ASM): aimed to facilitate the development of the airspace into one continuum that is flexible and reactive to short-term changes in airspace user needs.

In today's ATM, airspace is divided into ATC sectors typically handled by one air traffic controller (ATCO), able to control only a limited number of aircraft, denoted as "sector capacity." The existing method to attend any increase of traffic demand, in a given high-density airspace, is to proportionally increase the number of ATC sectors. By doing so in congested areas, the size of the resulting sectors becomes too small and then situation for which it is impracticable to handle air traffic could be reached, mainly due to the unfeasibility of execution of separation instructions inside the sector.

ATFCM measures frequently result in on-ground delays and/or rerouting. These measures are usually taken when air traffic demand exceeds capacity limits in any of the sectors or airports.

Although in the past ANSPs, airline operators, airports, and the ATFCM organizations have managed to cope with a significant traffic growth in an acceptably safe and expeditious manner, the current ATM system shows clear signs of saturation and inefficiency. In addition, an increased environmental awareness calls for more efficient operations based on better use of available technology. Moreover, in Europe, the economic crisis, imposes extra requirements on the European ATM system to reduce cost (e.g., according to Eurocontrol Performance Review Report 2005, ATM costs are estimated to be at 800 EUR/flight), and increase safety. Today's ATM processes are based on principles introduced more than 50 years ago and they are in high-density areas, as Europe, neither sufficiently geared nor flexible enough to adhere to the schedules of the commercial airspace users. Furthermore, national services providers suffer from low levels of interoperability and there is a lack of cooperative planning in the investment, development, and management of assets. This fragmentation of European ATM network and its lack of productivity imply a cost of more than 2 Billion Euros per year.[4]

In order to overcome previous limitations, Air Navigation Services Organizations in different parts of the world are promoting a paradigm shift in the way ATM is working today. Two relevant examples are SES/SESAR in Europe[5] and Next Gen[6] in USA.

To this end, SESAR has established six key features to achieve the ATM such a paradigm shift[5] (p. 7):

- moving from airspace toward 4D trajectory-based operations (TBOs),
- traffic synchronization (TS),
- dynamic ASM, facilitated by a central network, to enhance coordination between aviation authorities;
- moving toward a network-centric approach, underpinned by a system-wide information management (SWIM), such that all parties involved have access to relevant and most up-to-date flight information;
- airport integration and throughput and
- conflict management and automation.

Key to the SESAR and Next Gen concepts is the "*trajectory-based operation* (*TBO*)," based upon a 4D trajectory concept and, for the European program, the "*Business/Mission Trajectory*" principle in which the airspace users, air navigation service providers, and airport operators define together, through a collaborative process, the user-preferred flight path from gate to gate.

Summarizing, both SESAR and NextGen visions propose a new ATM system obtained by evolving the current situation from airspace-based operations toward a TBO, improving the A/C trajectories planning processes to reduce the tactical interventions, and building up a more distributed operational scenario (see Figure 1)

Current ATM is defined as "airspace based operations" because it gives to each "ATC sector" the key role to define the whole "airspace capacity," penalizing any exceeding demand. Meanwhile, the foreseen "trajectory based operations" claims for the highest degree of autonomy to aircraft to choose the trajectory they want to fly, promoting the required flexibility to ATM system to accommodate these demand by being a more proactive and distributed system.

European vision beyond SESAR/NextGen and the role of automation

When thinking beyond SESAR/NextGen, and the role of automation therein, three European vision documents are of primary importance and interest:

- "Flightpath 2050 Vision" document of the High-Level Group on Aviation Research of the European Commission (DG for Research and Innovation, DG for Mobility and Transport)[7]
- "Vision and Out of the Box" studies of the Advisory Council for Aeronautics Research in Europe (ACARE)[8,9]

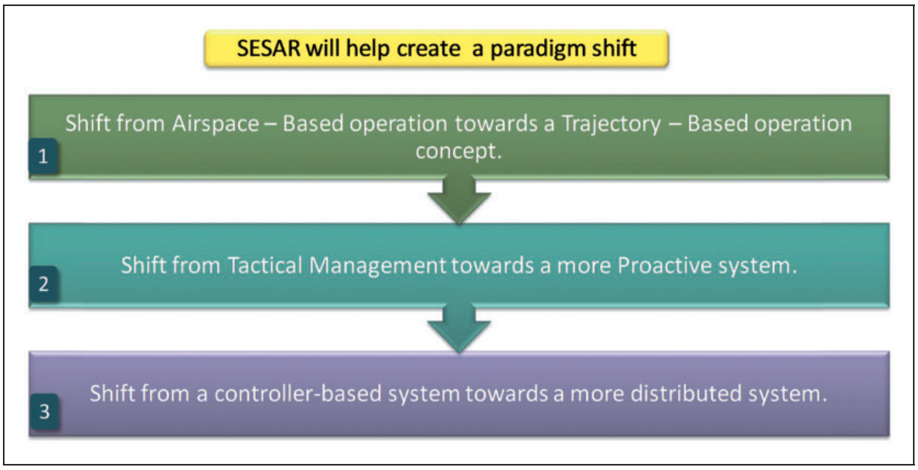

Figure 1. The pillars of the shift toward the new ATM system.

- "Vision and Full Automation" studies of the Association of European Research Establishments in Aeronautics (EREA).[10,11]

Below, the main ideas of these three innovative research councils/associations on the role and expected levels of automation in the air transport system of the far future (2050) are summarized.

In the FlightPath2050 document, a general remark is made with respect to the foresee role of automation in the future Air Transport System:

> The air transport network is able to cater for much greater traffic densities through new services based on ever higher degrees of automated flight management and control for all air vehicles. In addition to the benefits delivered to commercial air transport, precise navigation and on-board systems give all-weather, 24/7 capacity to rotorcraft and aircraft capable of door-to-door operation with limited infrastructure. All types of rotorcraft are capable of simultaneous, non-interfering approach to airports as part of regional networks including city vertiports and secondary, remote infrastructure, complying with local noise regulations. Automation has changed the roles of both the pilot and the air traffic controller. Their roles are now as strategic managers and hands-off supervisors, only intervening when necessary.[7] (p. 9).

Additionally formulates as key objective to maintaining and extending the European industrial leadership:

> System complexity and automation require highly-skilled staff and the best researchers, engineers and managers are attracted by the European aviation sector, which has the reputation for being a most highly desirable, attractive, challenging and rewarding career choice.

ACARE envisions much higher levels of automation for 2050, including—possibly—pilotless flight[8] (p. 67), but at the same time, ACARE seems critical about the feasibility of fully automated passenger flights. ACARE presents a view on ATC in 2050 that seems more in favor of noncontrolled airspace and free flight. A number of interesting questions are raised regarding a fully controlled and automated air traffic system, with aircraft being flown automatically under "ground control."

Next, the above-referred ACARE document discusses free flight as a viable alternative to full automation. In summary, ACARE raises questions about the flexibility of a fully automated system, its ability to handle unscheduled traffic and older aircraft, the means to transfer control between ground stations, and the liabilities in case of accident (who's responsible?). For passenger flights, ACARE seems to be more sympathetic toward the free-flight concept[8] (pp.67–69).

In contrast to ACARE, EREA envisions an ATS that is highly automated for both cargo and passengers.[11] This highly automated air transport system could have the following characteristics[10] (pp.12–13):

- With only a few exceptions, the notion of conventional piloting will be replaced by a "full automation" concept, along with the "4D contract."
- In constant contact with a *complete ground control and command system*, *cockpit-less aircraft* automatically follow flight paths adjusted to avoid major cities and decrease the distance/time flown for lower fuel consumption, without waiting, delays, or conflicts.
- Aircraft will no longer have a pilot aboard. However, people are still in the loop through two distinct functions:
  - One supervisor in the airplane (successor to the captain, who represents the airline and maintains on board authority) and

- One ground captain (transition of the controller's role to a supervisor tasked with managing emergency situations not provided for in the system). The ground captain can make strategic decisions (e.g., choice of routes, type of approach, alternate destination, etc), insofar as human reaction time is compatible with the type of decision needed.

In addition, EREA also pays attention to the way these high(er) levels of automation should be implemented. EREA envisions no hard transition but a gradual evolution toward ATS 2050 [30, slide 13]. Nevertheless, airlines, other operators, and the public should be convinced to embrace a fully automated system in 2050 (pilot-less flight)[10] (p. 28).

Finally, EREA gives a number of ideas about the technology required to support a highly/fully automated system. In summary, although ACARE questions outright the feasibility of a fully automated air transport system, EREA favors and envisions a highly and even fully automated (pilot-less) ATS. Cleary, these two visions contradict each other (whilst FlightPath2050 is less pronounced in its conclusion) as regard to the role and level of automation in ATM of the far future.

Hala! Research network,[12] based on these visions, proposes an innovative orientation for automation in ATM to meet the needs and demands of the air transport system of the (far) future. This proposal goes beyond SESAR and NextGen and encompasses all elements that play a role in the air transport system. The approach, depicted schematically in Figure 2, is to focus automation on ATM invariant processes and guide it toward a new role assignment, based on three interdependent criteria, having ''overall system performance'' as main driver for the resulting ''optimal'' ATM level of automation.

Paving the way toward this new vision for ATM, it has to be recognized that the main bottle neck for the current system is the high number of tactical decisions to be taken by the ATCOs and implemented by aircraft crew by using a weak (voice G/A communications) link (suffering, among other limitations, misunderstandings, and latencies).

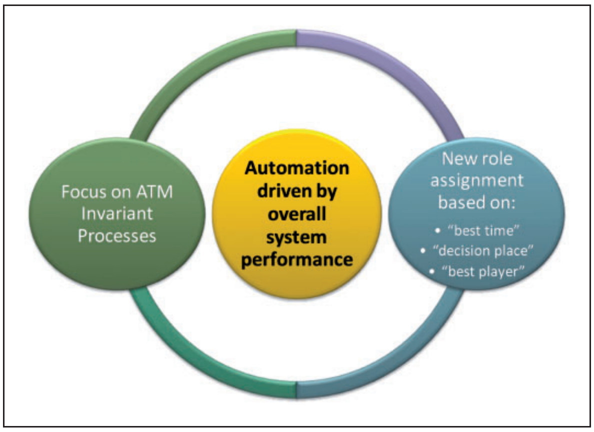

Figure 2. Automation in ATM shall be driven by system performance.

Evolution of automation science

Advances in information and communication technology, along the last decades, have led to a constant increase in the level of automation of control systems. These advances are relevant in other safety relevant domains such as power plants, chemical and industrial (e.g., plant control room), health care (intensive care units), and ground transportation (e.g., automatic train control). Some key issues related to the automation of control systems have been identified since the beginning of this process.

In automated systems and processes, function and tasks allocation[13] between human and machine has always been a point of controversy. In the context of automation, ''function allocation'' means that the agent (either human or machine), that is, best suited (based on some continuum of parameters) should perform the function. The basis for selection and grading of such parameters is at the heart of the issue of function allocation and has been subject to relevant investigation over the years.

One earliest static model of function allocation Men Are Better At—Machines Are Better At (MABA–MABA) list (see Figure 3) conceived by Fitts in 1951,[14] was notably based on material from ATC. This model states that functions are better suited for one agent or the other. The main issue based on this is to specify functions in order to allocate them properly.

Evolving from the above static approach, Parasuraman et al.[14] and others have proposed stepwise function allocation models of automation. Several levels have been specified (usually between 8 and 10) where the extremes denote full action performance by either human or computer, and the intermediate levels state to which degree the computer performs tasks and what is left for the human.

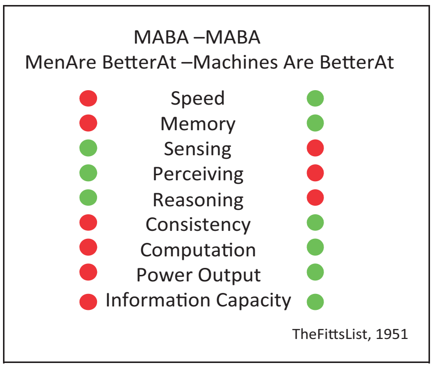

Figure 3. MABA–MABA list from Fitts.

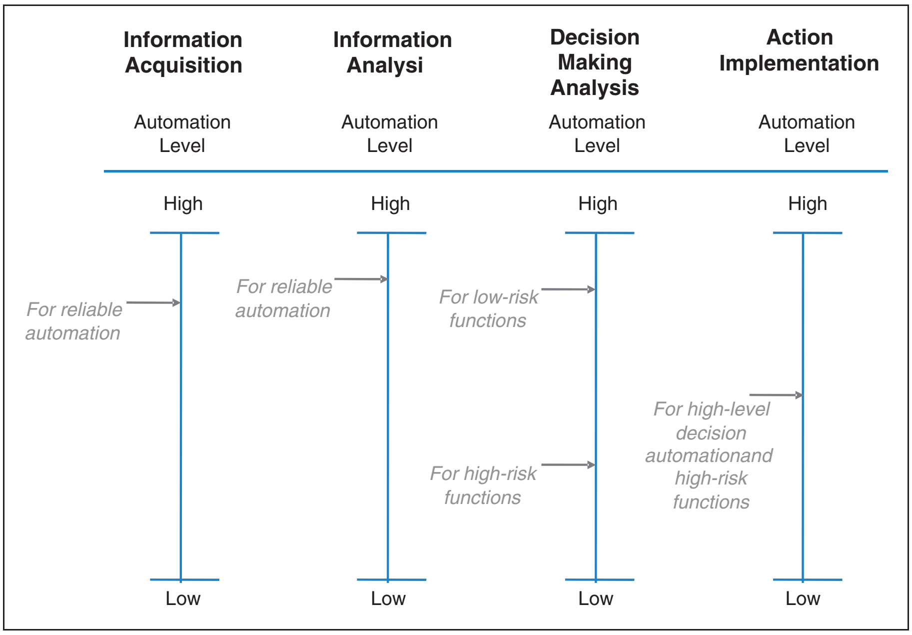

Figure 4. Levels of automation for independent tasks. Recommended types and levels for future ATC systems.

The original scale of levels of automation proposed in literature[14] by Wickens is focused on decision making and automation. If we focus our attention on ATC as control system, then the revised version proposed in literature[15] by Parasuraman can be more appropriate. This scale considers also the aspects of information gathering and analysis. In particular, the levels of automation are extended to four information processing stages:

1. Information acquisition,
2. Information analysis,
3. Decision making, and
4. Action.

Each stage has its own automation levels.[15] Following this approach, the application of Parasuraman's model has suggested the following achievable levels for future ATC like SESAR automation (see Figure 4):

- High levels of information acquisition and analysis automation can be pursued if the resulting system can be shown to be reliable.
- For decision and action automation, however, high levels should be implemented only for low-risk situations.
- For all other situations, the level of decision automation should not exceed the level of the computer suggesting (but not executing) a preferred alternative to the controller (indicated by the lower arrow).
- If relatively high-level decision automation is implemented in risky situations, it is recommended retaining some degree of human action by having a moderate level of action automation.

Increasing progress in computer science has enabled automation to a larger extent to evolve dynamically according to the needs of the situation, the load of the human operator, or the current status of the overall ATM system. Expert systems are increasingly developed that have some form of learning capability and anticipatory functionality that enable them to foresee the information needs of the human operator and to appropriately change the level of automation in order to obtain optimal system functionality.

Hollnagel[16] questioned the need for explicit task allocation as such in that some functions could benefit from a more fluid allocation. This was called function congruence corresponding to a continuous task transfer based on continuous mutual coordination between human and machine, much like optimal human team work is conducted.

A large amount of human factors and automation critical studies has been carried out during the 1980s and 1990s, when automation drawbacks emerged, among them; "ironies of automation,"[17] "Clumsy automation,"[18] and "Automation surprises" Starter et al.[19]

After several decades of research on automation, pursuing the reduction of the human involvement in system's functions and task, Parasuraman and Wickens recognized, in the article entitled "Humans: Still Vital After All These Years of Automation"[15] published in 2008, that this research strategy should be revisited.

Rasmussen[20] proposed in 1986 an integrated interpretation on the automation evolution (Figure 5). Under this vision, automation has evolved during the last part of the 20th century from mechanization,

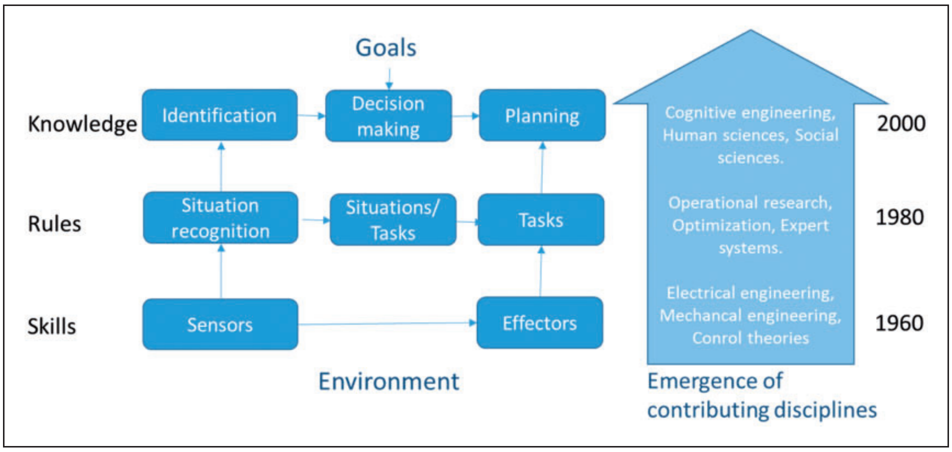

Figure 5. Ramussen automation evolution interpretation.

to electricity, to electronics and to software, the last one also referred as "computerization."

According to this interpretation, automation role has passed along three steps of maturity when acting between sensors and effectors from: skills, to rules, and finally, to knowledge. Encompassing this evolution, different areas of scientific and technical knowledge have been demanded as, electrical and mechanical engineering and control theories for the first step, operational research, optimization, and expert systems for the second step, and cognitive engineering, human, and social sciences, for the last one.

Boy[21] indicates that when assessing today these evolution, we must recognize that so far, technology maturity and maturity of practice were not sufficiently considered, being important factors that lead to a better definition of function allocation and finally automation. In particular, functions cannot be correctly allocated among humans and machines without a thorough identification of emerging cognitive functions, which lead to good design. Consequently, design is necessarily iterative, and supported by Modeling and Simulation (M&S) with humans in the loop, especially prior to product delivery. Effectiveness of M&S means make automation based on human-centered design possible and efficient.

Under this last interpretation, nowadays automation applied to multi-agent and safety critical systems, as ATM, is about integration of the different involved agents and organizations, considering their relationships within the overall system.

Each agent in this type of systems shall perform tasks that usually require a human cognitive function, where the role, context, and available resources are relevant in the performed activities, associated to the tasks.

Following this interpretation, automation require to build up carefully a model for such a system, identifying its different agents and their connections, where the separability among them will be crucial, facilitating the minimization of complexity in this connections, facilitating the liability issues, and introducing higher degrees of autonomy for each agent, such a model should provide emergent functions with different levels of maturity. The resulting global vision for such a system is like it is a "living organism."

This new perspective claims for the integration, understood this as an "orchestration" of the different agents taking each of them an expert, creative and flexible role, and maintaining at the same time the highest degree of autonomy, Within this context, each agent will be driven by "activity-level" rather than by a linear chain of command and a given prescriptive task allocation.

M&S gain within this context a key role in the process of automation for multi-agent and safety critical systems as ATM. Figure 6 shows the principle of a human system integration design based on M&S as an iterative process.

Modeling shall take into account people and organizations involved and other relevant systems interacting with each other. The modeling process produces a model that can be simulated, which in turn produces experimental data. Analysis of this information will produce identification of emerging properties, which enable learning about system use. The M&S design cycle shows that modeling is a closed-loop process that in turn enables system redesign, modification of people practices/profiles, and potential redefinition of other systems.

Summarizing Boy's approach, automation nowadays, applied to multi-agent and safety critical systems should be a "Human System Integration Design" process, which is particularly suitable to synthesize emerging properties of technology, organizations, and people (see Figure 7).

Shift from ATC sector–based operations toward TBO supported by automation

Figure 8 shows a representation of the ATM spatial/ temporal dimensions, including the pretactical

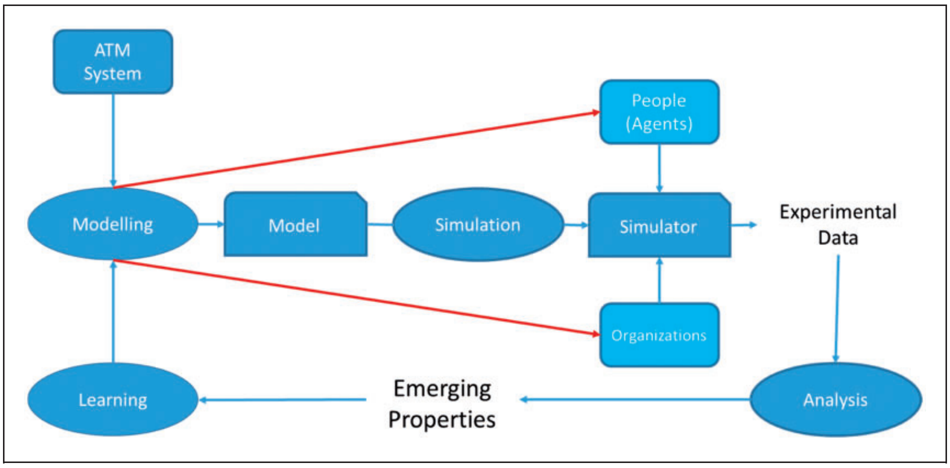

Figure 6. The M&S design cycles proposed by Boy.

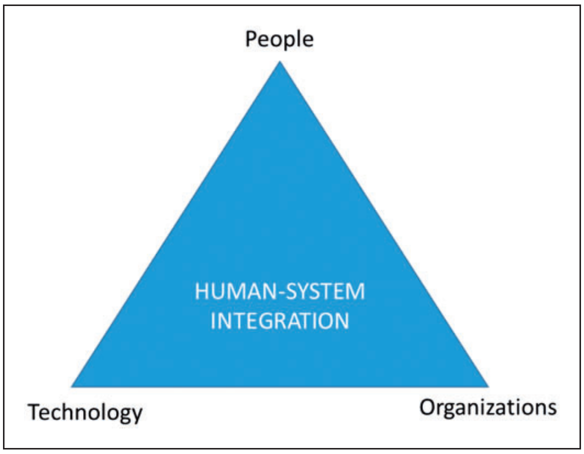

Figure 7. The human system integration design triangle.

demand/capacity balancing (DCB), where TS, conflict detection and resolution (CD&R), and exceptionally sense and avoid (S&A), are the applied operational time-based mechanisms, sometimes referred as "safety nets." Actions taking in this tactical scenario demand short-term reaction time, where generally only involved agents shall be aware of them.

Today's ATC is organized as an airspace-based operations, dividing the available airspace into volumes, as a tridimensional puzzle, so-called ATC sectors, and to assign the aircraft's separation responsibility among all aircraft inside to the ATCO working in this sector.

Each controller, using the "controller working position (CWP)" as human machine interface (HMI), controls all the aircraft contained within his ATC sector. ATCO and CWP can be considered as "control unit" of a typical human controlled system/process. As shown in Figure 9, this is a typical "single agent" controlled process.

This operational scenario exhibits maximized separability which allows, as important advantages, the minimization of both liability problems and system complexity. But, on the contrary, it concentrates operational tactical tasks on this "control unit," being the cause of the current main ATM bottleneck.

During the last decades, automation have paid a relevant effort to the development of new tools to improve flight plans and surveillance information provided to ATCO agent, through the flight plans processing systems and radar data processing systems. Furthermore, some progress has also been registered in the COMMS (voice and data communications) information acquisition. As a result, current CWPs supplies now a more accurate and reliable information to ATCOs, although the final added value, in terms of capacity, efficiency, and safety, is not perceptible.

The main reason for this very limited efficiency evolution is the amount of tactical tasks allocated to this single agent. These remain essentially the same and, although nowadays, as said before, new CWP provides decision support tools (DSTs) (mainly alerting systems) to help in controller's task, it is not enough to maintain the capacity/safety performance in a more efficiently scenario.

As shown in Figure 8, the possibilities to reduce the number ATCO tactical tasks (mainly devoted to TS and CD&R), are:

- Reorganizing function/task allocation within the ATC centers (ATCCs). Currently, operational activities are organized upon "ATC sector," managed by an executive controller supported (usually) by a planning/assistance controller, both using the CWP. It is possible to reorganize this operational scheme by other, like, executive controller/multi-sector planner, the last one sometimes referred as "area manager."
- Transferring some TS tasks to a centralized organization (as network manager, using European terminology). This option advocates for a more centralized ATM system, where planning efforts, to balance traffic demand and ATC capacity, go closer to the operational phase, participating in

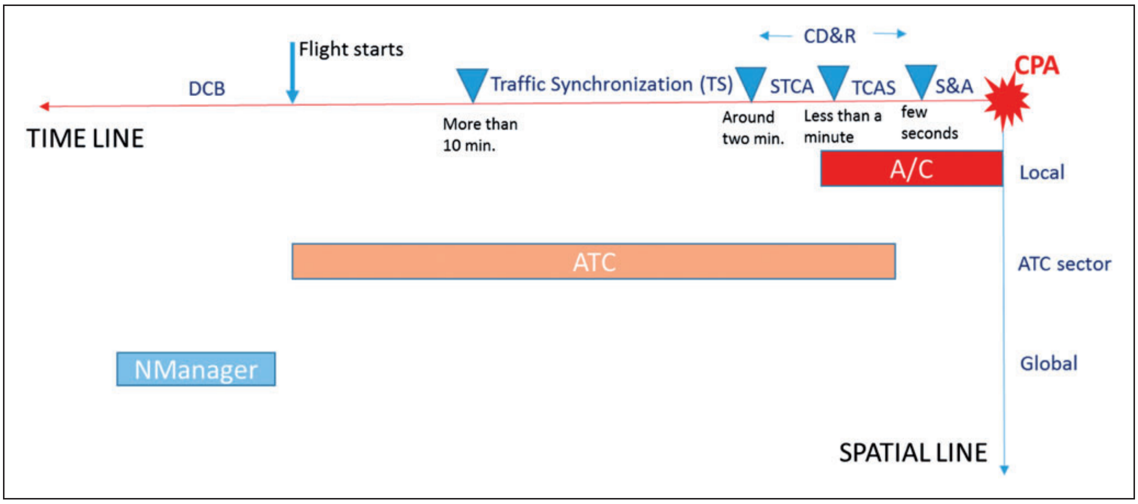

Figure 8. ATM resources to avoid separation infringement at "Closest Point of Approach (CPA)" among each aircraft flying within controlled airspace.

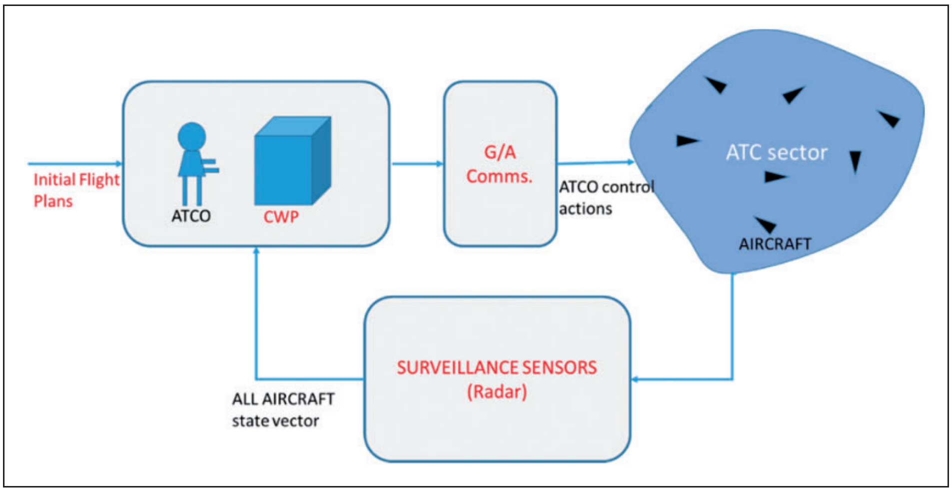

Figure 9. ATC sector represented as a single-agent controlled process.

the trajectory management even when aircrafts are in flight.

- Transferring some TS and CD&R tasks to the aircraft.[22] But, in this case, the degree of authority the operator has over the trajectory flown by the aircraft, and his degree of responsibility has to ensure safe operations. Under this assumption, autonomy provides the operator the independence to define and change the trajectory. Responsibility compels the operator to independently ensure that its trajectory does not breach established separation criteria from other traffic. Strong safety requirement will be demanded under these operational mode, higher than the currently applied for VFRs.

To analyze any of the above possibilities, the classical "single agent" approach as basic operational scenario to promote automation has to be changed, it has to be broaden to cover all ATM operational processes. A new model is then required and, from this new operational vision, the new challenges for automation could be inferred.

The global new vision should consider ATM as: "System devoted to provide compatible and efficient trajectory for all airspace users." The ATM context is then composed by these airspace users but as well, by services providers, devoted to support them, assuming that the airspace has uncertainties, limitations, and constrains, that users need to overcome to maintain a safely and efficient airspace use.

Figure 10 shows the essential actors participating in the ATM processes, where the operational ATM context is enclosed in the dotted box. Services providers are here split into two levels:

- ATM services providers, including airports
- CNS and aeronautical information providers.

Being ATM services those focused in providing real-time added value operational support to all

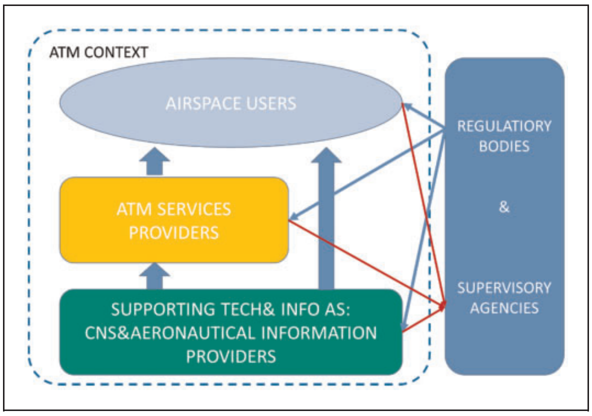

Figure 10. The main ATM actors.

airspace users as DCB, TS, and CD&R. Meanwhile, CNS and aeronautical information are supporting technical and information services required by both airspace users and ATM services providers.

Within this ATM context, the high-level operational architecture can be presented as indicated in Figure 11. It shows the links and roles played by the different main actors in the trajectories compatibility planning and execution processes. The upper part, from left to right, shows involved agents[b] requiring a holistic vision about airspace and infrastructure status, AOC fleet status, and airspace and airports operational (real-time) capacity, respectively.

The lower part of the Figure 11 shows the tactical reactive phase applied to aircraft trajectory while flying, where TS, CD&R, and exceptionally S&A, are the operational mechanisms to be applied. Actions taking in this case demand short-term reaction time, where generally only involved agents will be aware of them.

The above operational architecture states that future ATM has to overcome the reductionist vision of a system geared basically by ATC, passively supported by technical and planning enablers. Modeled instead as a complex multi-agent system, where automation should pay attention at global level, as well as its specific and essential processes.

The challenges of automation applied to ATM, aligned with the vision presented above, consider ATM as a sociotechnical multi-agent system, where each agent should have a *high level of autonomy*, but, maintaining simultaneously a *high level of "orchestration."*

This recognition has already been implicitly accepted by SESAR and NexGen. Sociotechnical by assuming that humans will remain in the core of the system. Multi-agent, by considering SWIM as required technical enabler, involving all actors. Orchestrated by introducing collaborative decision making (CDM) as basic concept for an efficient ATM system.

When looking for ATCO's tactical interventions tasks reduction, the above architecture exhibits five ATM main actors/agents (rounded boxes) all involved in linked roles, two at proactive level: network manager and aircraft operations centers (AOCs) fleet management entities, two at reactive level: ATCC and A/Cs, and one involved in both phases: airport operations.

More precisely, the new multi-agent ATM model shall be mainly based on trajectories management, where its goal can be stated as follows[c] (see Figure 12):

System devoted to provide compatible and efficient trajectory for all airspace users.

Composed by an operational architecture with two mayor time layers (Figure 12): DCB planning phase and reactive or tactical trajectory management phase. Additionally, ATM is highly coupled with airports, as nodal points of the system. Finally, communications, navigation and surveillance, as well as aeronautical relevant information, are fundamental enablers.

Automation of this coupled multi-agent system involves support tools devoted to maximize their autonomy (by reducing the amount of coupled tasks among them) and the level of orchestration (by increasing their institutional, spatial, and temporal cohesion). A key element to this end is to recognize that all ATM-relevant interchanged information among different agents is directly related to aircraft trajectories.

Furthermore, all the ATM activities will be driven, as any other management activity, by invariants general objectives and constrains, determined respectively by its goals (what the ATM system pursues), and limitations (what are the inherent operational limits affecting the ATM system), as showed in Figure 13.

The goals of ATM are, in broad sense, twofold; to provide the required separation between aircraft that permits to deliver the required safety, and at the same time, to maintain air transport competitive by providing efficiency to users, being environmentally friendly and socially valuable.

Limitations of ATM are also twofold. On the one hand, considering that aircrafts are supported by the air, filling in atmosphere, its physical properties will significantly affect the flight's behavior. Similarly, while the air transport payload is usually taken and delivered at airports, airport capacity will be taken as ATM constraint.

Operational changes will probably be supported by new roles for managing aircraft trajectories, including separation provision and trajectory de-confliction,

[b]Agents: operational elements of the air traffic management (ATM) system performing a clearly identified set of task.

[c]This is the answer to the trajectory-based operations (TBOs) operational concept.

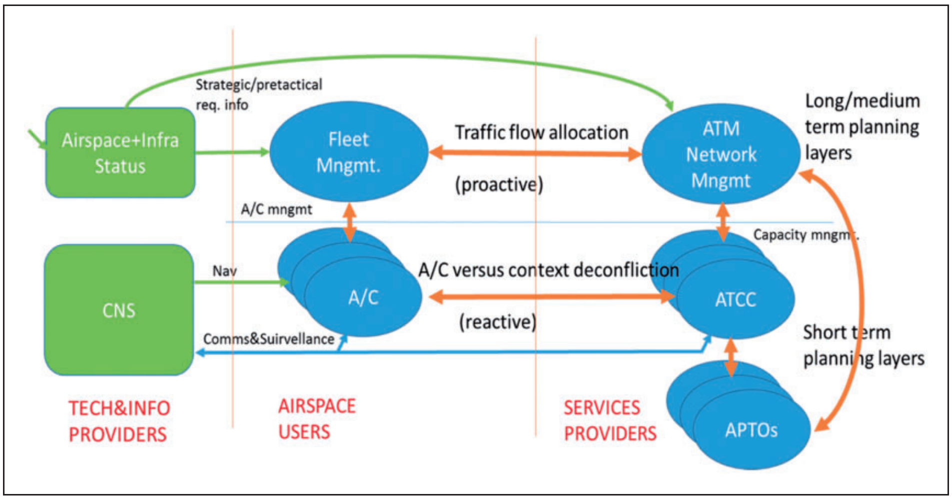

Figure 11. Operational ATM architecture showing actors and agents.

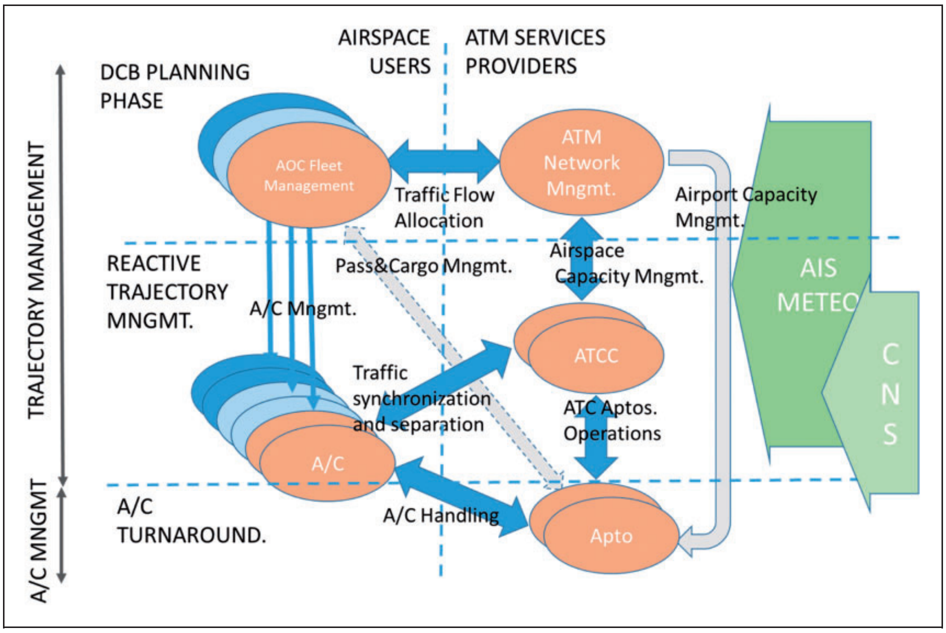

Figure 12. Operational elements of the ATM and their links.

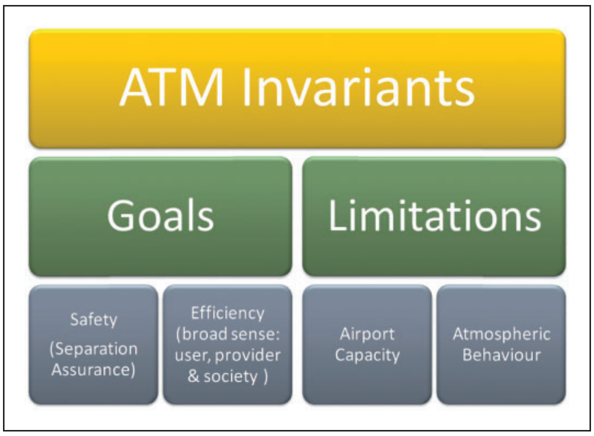

Figure 13. ATM invariant as starting point.

leading toward adopted procedures for both the ATM services providers and aircraft operators.

The new roles for the different actors will be based on conceptual or theoretical considerations and the general assumption: "humans will still be central cornerstones as managers and decision-makers." Nevertheless, the only principle about the assignments of new roles should be that the "decision about aircraft trajectories could be taken by the actor that is ideally placed at each moment and for the given scenario to take such a decision" and the impact on overall system performances should be the main driver.

Evolution from a purely tactical intervention model toward a more strategic trajectory management concept and progressive introduction of more autonomous and orchestrated operation are the key

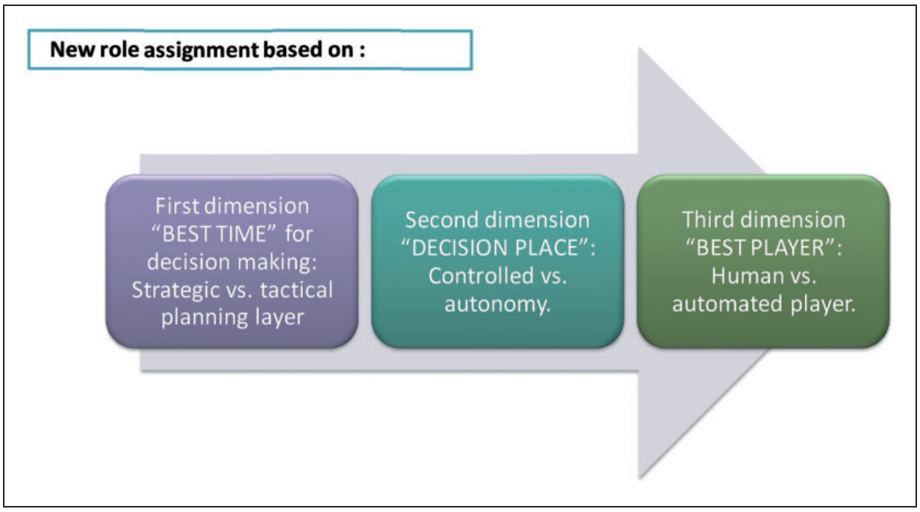

Figure 14. The three dimensions involved in the identification of new roles assignments.

concepts. As mentioned above, implementation of these future ATM will change the human and organizations roles, as well as their relationship with the automated processes. Who is the best player against overall system performance should be the choice criterion.

The choice of this best player will be derived from the consideration of the three decision criteria identified in Figure 14. The three sequential dimensions involved in the identification of new roles assignment are:

- Optimal decision time for all and any relevant event in ATM, which involves strategic vs. tactical layer;
- Optimal decision place, which involves centric vs. autonomous consideration to decide, which place is suited best to take the required decision;
- Optimal decision player, which involves human vs. automated player considerations.

Under this approach, only decision-making tasks are considered as "key tasks" of the process, it is expected that other tasks, associated to the process, will be easily allocated once the decision task has been established.

Decision time needs to be found along the various required functions that are carried out by pilots, controllers, and other operators (on ground) on the pre-operational level. The general principle will be to move decision time toward a certain more strategic handling of ATM events while improving the efficiency of these task, despite some increase of data uncertainty will be expected.

In general terms, to expand the planning, time frame is positive to facilitate the management of the involved resources, but it brings us, as a consequence, less accuracy in the information, particularly those related to the estimation of atmospheric behavior and the development of costly centralized functions. Thus, the "best time" for trajectory planning should be established making some kind of trade-off between both, better use of available resources on one side, and accuracy of the data required for trajectory prediction and the cost of this new centralized functions on the other side.

Autonomy of decision supported by higher level of automation arises as the best option when unpredictable events occur with low available reaction time, low number of aircraft, and/or small spatial affected area. There are two main reasons for that: corrective autonomous decision usually needs smaller reaction time and, at the same time, uses fewer amounts of resources (only those available by the affected aircraft), thereby reducing the costs. Furthermore, the limited number of affected aircraft and the small dimensions of the area, the less probability of propagation of secondary effects.

In the other extreme, when the event involves a significant number of aircraft as well as an extensive area, if reaction time permits, the global picture for any compensatory action using centric systems, where humans using DST play an important role, arises as the best option. The main reason is that autonomous and automated reaction could propagate secondary effects, introducing potential instability in the global air traffic system, affecting safety level. Additionally, these situations usually involve factors that complicate the management in a fully autonomous/automated ATM scenario.

In all cases, the level of involvement of today's ATM operator into the design of new ATM functions shall be increased and traded off with regard to achievable innovation. Intelligent cross-border think tank strategies shall be considered including "self-generated" strategies from artificial intelligence systems.

Although the starting point for the new human role assignment is considered inside the current SESAR/NextGen concepts of operations, every current ATM system process hampering innovation will be subject to investigation and alteration. This refers to aspects generated from already foreseeable innovative ATM technologies, well-established safety requirements for system certification, and in general, the human-centered perspective. As such, future functions and procedures being allocated to the human may be quite different from those performed in ATM today.

The increasing traffic will also drive the airport ground resources to critical levels with regard to infrastructure and traffic-handling procedures on ground. Once again, increased automation through well-designed functions acting at the right level, time, and context is required to adapt resources to the future ATM system being aware that currently, this part of the ATM system is not entirely centered designed but designed in parts well distributed (e.g., between airport operator and ground handling or maintenance functions).

Additionally, trajectory management in scenarios where no capacity restrictions or constraints are derived from human intervention, best actor (human vs. machine) is then envisaged as a permanent trade-off between safety and aircraft performance. Even in this trade-off, it will require an intense enhancement of integrated automation and complexity management support.

Taking into consideration the above as key cornerstone, it is feasible to identify two challenging broad areas of especial interest, from the research point of view, as crucial and complementary issues.

- Aircraft trajectory hierarchal, spatial, and temporal cohesion among the different ATM organizations and agents, considered as part of a sociotechnical multi-agent system, as key element for an efficient integrated ATM,
- Trajectory management, including trajectory optimization, DCB, TS safety barriers, detect and avoid systems, autonomy of flight/vs, centralized services provision, latency effects on all kind of agents remotely controlled are, among others, key research issues, that involves especially remotely piloted aircraft systems (RPASs).

Conclusions and proposals

Global challenges in ATM, described in dedicated documents issued by reference institutions as: high level group (HLG) on Aviation Research, ACARE, and EREA reveal different visions about the levels of automation to be reached in the long-term horizon (say, 2050), but all of them coincides to consider that the future system will deeply change the role of humans, from controlling functions/tasks to manage/supervise ATM subsystems, proposing a more integrated global ATM system while supporting more autonomous operations.

Paving the way toward this global challenge requires a stepwise approach by considering ATM as a time continuous and spatial worldwide system, where any change shall deliver overall system performance in a smoothly and harmonized manner.

Hala! proposes to evolve toward higher level of automation ATM by providing decision tools delivering compatible and efficient trajectories for all airspace users, enhancing the hierarchical, spatial, and temporal cohesion among the different organizations/agents involved in the planning and operational phases of the trajectory management process.

To this end, automation shall also provide decision tools within the trajectory management process itself focused on trajectory optimization, TS, safety nets behavior, and compatibility between autonomy of flights and centralized services provision.

All previous goals will demand a human system integration approach, where emerging properties of automation are derived from the behavior of people, organizations, and technology under the proposed changes. M&S gain a key role in this process of automation, recognizing ATM as a sociotechnical multi-agent system.

ATM will then evolve toward a more orchestrated system (giving more relevance to the CDM concept and supported by SWIM) where autonomy for the different agents shall emerge by applying supporting technologies as HMI and robotics.

Associated to the two HALA! general ATM-oriented challenges presented previously, there are related scientific challenges dealing with specific very relevant issues associated to automation processes as:

- Resilience and control system degradation. Areas of investigation include: designing resilient systems and defining recovery paths in degraded modes of operation; monitoring for system degradation; assessing the ability and prerequisites for human role in recovery from system degradation such as in; risk and safety assessment techniques.
- Ability to formalize, understand, and model the system to be controlled in all possible normal and abnormal operational conditions, and to face possible unexpected situations. This is an essential prerequisite to design control systems that are effective and resilient, that is, able to maintain acceptable performances in all conditions. While several advancements have been achieved in different domains of application that already use high degrees of automation. Their contribution is limited because those domains are less ''open'' and complex than ATM, with a significant lower level of operational variability.
- The adequateness and correctness of the human role in the control system, in particular the ability to ensure human motivation, trust, and dependence on automation, and the ability to maintain

situational awareness. With automation, humans are never completely removed, but assigned to supervision and monitoring functions, especially to deal with possible unforeseen operational conditions and malfunctions. In such a role, humans, even if removed from the direct control loop, shall maintain situational awareness and understanding of the automated system decisions. Some recent published works contribute to this point by discussing the problem of modeling the human role in such a context, evaluation of the adequateness of automation to support humans, and the provision of support for the evaluation of alternative design options.

- Responsive and adaptive automation. Automation is normally considered as a "static condition" predefined during the design of control systems. However, this is not necessarily the appropriate solution. Responsive and adaptive automation tries to vary function allocation during system operation on the basis of the human needs, either on the basis of his request or automatically. A variety of system providing different levels of automated support can be offered to the human allowing him to choose the level of help that is needed. Alternatively, automated aid can be provided automatically to reduce workload when the human is detected to be in overload, or to boost situational awareness when considered too low or when the need to deal with specific critical situations arises.
- Change management. The main area is managing change and transition from both human and technological perspectives when transiting to higher degrees of automation and introducing new technology.

Above challenges represent the main goal supporting the idea that any research activity, devoted to promote an automation applied to ATM system, has to give a clear response to all the following questions:

- Are the A/C trajectories as "virtual lines" (planned, in flight, postflight) the main subject of the research?
- What is the expected time frame horizon (before, inflight, after flight) to which the activity is thought to be applied?
- Is it devoted to improve trajectories hierarchal, spatial, and temporal cohesion among the different ATM organizations/agents?
- What are the required sources of information?
- Who and with which role intervene the involved operational agents?
- Are the research activity trying to reduce the ATC tactical interventions by improving the planning DCB? Or is it trying to reduce this intervention under TS or CD&R conditions by transferring tasks from ATC to A/C?

First question "are the A/C trajectories considered virtual lines the main subject of the research?" should always be positively answered. ATM system does not need any additional long-term research focused on the development of supporting tactical interventions. Nowadays exist Traffic Collision Avoidance System (TCAS, on board safety net) and Short-Term Conflict Alert (STCA, on ground ATC safety net) and, although still exist some open issues related to this systems, most of them are related to the hierarchal, spatial, and temporal cohesion between the different agents acting under TCAS or STCA situations, and then is not a question of how to control the involved aircraft, but about how to enhance the cohesion to manage their trajectories under this situation among the different involved agents. Exception to this criteria should be applied when the research activity is focused on the S&A layer support tools applied to RPAS.

Second question, regarding to "the expected operational time frame horizon to which the activity is thought to be applied," might have different answers, short-, medium-, or long-term horizons, but it should not cover several temporal time frames when it is related to trajectory management issues, unless the research activity is devoted to improve the temporal cohesion among the different planning layers.

Third question, regarding to improve trajectories hierarchal, spatial, and temporal cohesion among the different ATM agents, is closed related to who is the best player against overall system performance from the consideration of the three decision criteria, best time, best place, best actor/agent, discussed previously. Research activities within this context should reveal not only when, where, and who shall perform a given ATM operational function/task, proposing innovative operational architectures, but as well and above all, developing tools to link them, delivering maximized autonomy and orchestration among the different actors and agents. The answer to this question can be positive or negative. But in the last case, the research activity shall be clearly devoted to some of the long-term research open issues related directly to the trajectory management problem.

Fourth question, about what are the required sources of information, shall give, as answer, the level of maturity (in terms of accessibility, reliability, integrity, and accuracy) demanded for the required information as input for the process/subsystem where automation is proposed to be applied. Data, obtained from sensor's raw observations, have to be transformed into information, analyzing this data by using different filtering techniques. Although this filtered information can now be applied for control purposes (as it happens in conventional feedback and human supervisory control systems, acting then in the short term), they will still normally be unsuitable for higher levels of automation, where cognitive activities and managerial decision taking are usually involved. It is then important to know whether the research activity is requiring information neither available today nor in the medium term, obtaining then, in the best case, unrealistic outcomes.

Regarding the fifth question, who and with which role intervene the involved operational agents, shall by answered specifying who (what agent) has to implement any particular task under any particular situation (demanding dynamic role assignments). Furthermore, additionally the level of interconnections among agents under all kind of conditions shall also be clarified. From these analyses, the feasibility level of the proposed supporting tools will be derived.

Lastly, the sixth question, asking if the research activity is trying to reduce the ATC tactical interventions by improving the planning DCB, TS, or CD&R condition by transferring some current tasks assigned to ATC to other agents, recognizes that the main bottleneck (in high-density areas) in the current ATM system is the large amount of tactical interventions, involving time pressure for controller's actions, limiting airspace capacity and safety, resulting in a lack of ATM efficiency and limiting future air traffic growth. In this respect, demanded research automation effort should provide a more relaxed working environment for the controllers either by improving the medium- and long-term DCB processes, involving other managerial actors/agents, or either by transferring to the A/C some tactical synchronizing or separation tasks.

All the above remark the enormous effort that will be demanded from the scientific community to facilitate the change from the current ATM (supported basically by ATC) to the more distributed ATM. Formally, current system has been developed by using only the spatial dimensions (i.e., ATC sector physical boundaries, ATC sector capacity limit, horizontal and vertical separation minima, spatial fixed waypoints and ATS routes, etc.) and only two main operational agents, the controller and the A/C crew.

Differently, future ATM shall involve additionally two more dimensions, new actors and their operational agents (i.e., multi-sector planner, network managers, AOCs agents, RPASs, etc.) and time (i.e., reference business trajectory, airspace temporal occupancy, time separation, dynamics waypoints and routes, etc.). This new multidimensional and multiagent ATM scenario involves a complete paradigm shift that has to be performed with continuity, demanding then the permanent involvement of the organizations and humans operating the current system, as pioneers of the new foreseen system.

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