Different paths to automation

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1 Introduction

Does the future of Air Traffic Management lie in automation? It looks like flying a plane from point A to point B is just a mathematical problem involving optimization under constraints (other planes), flow management on networks, etc. So, it should probably be handled automatically by computers, either on board or on the ground. Moreover, it is also clear that human capacity for information handling and computation is severely limited and that, sooner or later, it will be impossible to increase airspace capacity if we keep human as effective and exclusive actors in the control loop.

But, even if we are over-optimistic, we can not expect any automated ATC[1] system before at least twenty or thirty years: the more recent prototypes of automated systems, such as the ARC2000 system [K+89], rely heavily on many assumptions that are not met today, such as FMS-4D[2] aboard all planes, etc. Moreover, these assumptions will not be met for quite a long time: there are many different types of airplanes (commercial, private, etc.) and fitting out each and every of them with such expensive and complex equipment is not to be expected on short terms.

There are also some technical questions about automation that have to be answered: there have been no serious theoretical studies on the capacities of automated systems, and there is still no clear design of what will be the automated system of years 2020–2040: many different alternatives exist (4D tubes [K+89], reactive systems [Zeg93], distributed resolutions on board, resolutions on the ground [NFC+83], etc.) Moreover, an ATM control system is a patchwork of many different tasks [AC92], some of which already being good candidates for automation, while others will still be impossible to automate for quite a long time.

So we have to define a way to go from the current, existing system, to a system that will not be ready before at least 2020, the design of which being still uncertain. This *transition phase* is certainly the major thing to work on. In this paper, we are trying to show that there are many different ways to go from the existing system to an automated system, each way having drawbacks and advantages. Moreover, during this evolution, the role of the pilot and the role of the controller will both change.

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[1] Air Traffic Control

[2] A Flight Management System that can follow 4D trajectories.

2 Is automation possible?

2.1 Technical problems

Almost all projects working on automation or enhancement of control techniques have to solve the same kind of problems. We are going to shortly list them. Then we will see how each approach try to solve each of these problems.

Trajectory prediction: each and every system has to have a reliable trajectory prediction, but there are a lot of different parameters that make trajectory prediction a difficult business. Some of these parameters are pure technical problems, some others are structural and are not easy to solve:

- **weather forecast parameters:** they have to be quite well known in order to be able to compute an acute trajectory. An error of 10kts on a wind will give an offset of 13Nm[3] on a 20 minutes trajectory prediction.
- **Aircraft model:** having a good aircraft model is a difficult task. One of the problem difficult to manage is the fact that the same plane will not always fly the same way according to the company, the range of the flight, etc. The aircraft model needs lot of information that must be gathered efficiently.
- **Aircraft equipment:** a plane with a FMS-4D associated with a GPS[4] or an inertial system can much accurately follow his route than a plane using a VOR[5]. Different planes

[3] Nautical mile

[4] Global Positionning System

[5] VHF Omni-Range beacon.

have different equipments and consequently have different accuracies when following a given trajectory. This factor is not going to change for quite a long time.

Pilot behavior: it is certainly the most important parameter and unfortunately also the most difficult to anticipate. Different pilots will execute differently the same control orders. For example, if a pilot is asked to climb in order to be at a given level at a given beacon, he can either climb as fast as possible and then fly level, or climb smoothly and regularly to the requested level. Another classical example is a pilot who switches on or off air conditioning: this can affect the climb rate by almost 10%. While pilots will be in the loop, it will be almost impossible to have an acute trajectory prediction.

Conflict detection: if we consider the trajectory prediction problem solved, trajectory prediction must be used to detect conflicts that will or may arise. Conflict detection becomes, of course, much more difficult when we want to detect conflict long time before they will occur. For example, to have a 20 minutes conflict detection, we need an excellent trajectory prediction if we do not want to have too many false alarms.

Clustering: as soon as conflicts are detected, they have to be solved. Solving one conflict can induce modifications that may give birth to a new conflict, or modify the resolution of another conflict. The set of planes that are inter-related in terms of conflict resolution is called a cluster (according to the AERA-3[6] terminology). Each cluster must then be handled globally, but resolution in each cluster is independent to other clusters.

Conflict resolution: as soon as the set of planes on which we have to work is clearly defined, the conflict has to be solved. There are two decisions that have to be made: what to do and when to proceed. Moreover, there are lot of constraints that must be met when building planes trajectories:

- changing level only if no other solutions is possible
- asking planes to change speed to solve a conflict is almost impossible
- one turning point other 30 to 50 Nm is the maximum that a plane can handle
- trajectories should be optimal in terms of time and space.

Free routes: giving free routes to planes or keeping them on pre-defined routes is a well known problem that has not been solved yet. There are studies on the subject but none of them is really clear on the impact of each solution.

Security: security is the major outcome of air traffic control.

2.2 Which Role for man in an automated system?

In fact, different roles of man must be considered [gr93]

In this sections, we will summarize the discussion already begun [AC92] about general criteria pertinent to the man/machine tasks repartition. Reliability is one of the most critical concept in Air Traffic Management. In complex systems, it is well known that about 80% of errors are human errors [Hol91]. A fully automated system will therefore be more reliable than a system keeping a man in the decision process. One of the great advantages of human beings over computers is their creativity when faced with a new problem and their ability to react to unexpected situations. On the other hand, computers are extremely efficient at performing repetitive and boring tasks. So, when choosing to automate or not a given process, or a part of the process, it is necessary to consider the features of the process in terms of creativity and repetitiveness. A process requiring creativity (such as theorem proving) is a poor candidate for automation, a repetitive task an excellent one.

Human beings are excellent at tasks requiring associative processing, or, said otherwise, reasoning by analogies, or recognition of classical patterns. This is a very general capacity, that ranges from character or sound interpretation to conflict resolution techniques, which, like almost any human reasoning, use analogies to find a solution. But human beings are very bad at pure computation. They are unable to calculate precise trajectories, integrate wind speed modifications, etc. On the other hand, computers are very bad at recognition or analogies. Even if some recent techniques try to slightly fill the gap, they do not provide for the moment an answer to this problem. But computers are excellent at pure computation.

A very computation-oriented task is an excellent candidate for automation, while a task requiring analogies or recognition based reasoning is a poor candidate.

Keeping human operators in the loop of control introduces interfaces between one operator on one side, and another operator or a computer on the other side. Information has to go through that interface, whether it is human dialogue, data presentation or command input. Whatever the respective "computing power" of both sides can be, the capacity of the interface to deliver the correct amount (or rate) of information is a serious issue and it should be kept in mind that limits exist.

Partially automating a given task might induce perverse effects, such as the loss of experience and skill for the human operators. Sharing or allotting tasks to computers and human beings must take this important parameter into account. There are many solutions

[6] Automated En Route ATC

that can be considered: one can consider that the machine is fully in charge of the task, and that the human operator will have no further work to do, except supervision of the system; then "keeping up with one's skill" has no meaning, because the supervision of a system is a new skill that must be developed to replace the original one. It is also heavily probable that this new skill corresponds to new user interfaces dedicated at supervision: exploration and troubleshooting are not similar to controlling, and controlling in emergency situations only is not similar to regular controlling.

One might also consider a dynamic allocation of tasks between the human operator and the computer, given the current workload, and other parameters. This is an attractive approach, but it must still be proved that it is possible to correctly allocate tasks.

One might also decide that the man must remain in charge of all decisions to be able to keep up with one's skill, and only present him informations to be able to take such decisions. With such an approach, the human operator and its low capacity for data processing will remain the bottleneck of the system, a bottleneck that should have to be removed sooner or later. Moreover, this implies that we are able to present only meaningful and useful informations for the operator, if we do not want to overflow him with data. It is a difficult work, and a work which will require long and difficult experiments and validations.

3 Some examples of prospective projects

3.1 Full automation (ARC2000)

The ARC2000 scenario proposes the concept of a fully automated system[K+89]: "it will become more and more difficult, if not impossible, to accommodate the ever increasing traffic demand with the existing traffic management capacity by increasing the number of controlled air volumes, air traffic controllers, and radio frequencies. Hence new concepts have to be investigated to overcome the existing capacity and efficiency restrictions, frequently caused by human performance limitations."

In order to make optimum use of the available resources, air traffic is planned as precisely as possible at any given moments. In ARC2000, flight plans are a description of *complete* trajectories, from the present aircraft position to its destination airport. These trajectories are negotiated and agreed between ground (ATC system) and aircraft (FMS-4D). These trajectories are as optimum as possible in terms of time and fuel, and free of certain conflicts. They provide some flexibility for uncertain proximities or potential constraints: they can be considered as 4D-tubes[7] of a given diameter. The flight plan can be seen as a contract between the ground system and the on-board FMS system. If, for any reasons, one of the agents had to change this contract, a new negotiation would take place to reach a new agreement.

The ARC2000 planning strategy is to guarantee conflict free trajectories for the next 20 minutes: a balance must always be found between planning conflict-free trajectories long in advance, or postpone that and have to revise trajectories continuously. The compromise in ARC2000 is to plan the whole trajectory as conflict free as possible, and to monitor proximities, of which certain may become potential conflicts. So, with a minimum of 20 to 30 minutes in advance, the traffic situation is organized as conflict free except for some proximities under special monitoring; and beyond this period, only those situations where a potential conflict is firmly diagnosed may be subject to the reorganization of flights.

The ARC-2000 system can not be considered as a system optimizing the *global* system, i.e. all planes trajectories. In fact, each time a new plane is introduced in ARC2000, its optimal trajectory is computed *given all the other planes trajectories which have already been computed*, these trajectories being the constraints. So, the last plane to come into the system is also the most penalized. This has the advantage, however, to reduce the number of computations, the complexity of the algorithm in charge of calculating trajectories, and to diminish the number of flight plan modifications.

The ARC2000 system is very difficult to integrate in a transition scenario. As it is a free-route, completely automated system, it is definitely in opposition with all standard work procedures in use today. Controllers have definitely to be out of the control loop in such a system . The problem is to know how we could pass from a classical, human centered system to such an automated system.

3.2 Cognitive Modeling (ERATO)

ERATO[8] is a project aimed at giving a cognitive modeling of the human operator in order to give him aiding tools to perform resolution. The main idea is to maintain the controller qualification, while enhancing his capacity in terms of number of conflict he can handle by providing him relevant information. The project allows to define some cooperative tools taking advantage of a suitable information filtering, that can be considered as a controller's electronic assistant [Ler93].

This approach has a great advantage: its acceptance factor; it will not change the way controllers already work, and is then much easier to include in an existing ATC system.

In terms of transition to an automated system, this approach is exactly on the opposite side compared to ARC2000. There is currently no way to automate anything following this approach, and, in fact, automation

[7] A 4D tube is a trajectory represented in 4 dimensions. This trajectory is then enlarged to take into account uncertainties on plane positioning and speed, or rate of climb/descent, etc.

[8] En Route Air Traffic Organizer.

is definitely in opposition with the philosophy of this system. Other drawbacks of this approach are discussed in section 4.2.2 and will not be discussed here again.

3.3 The AERAs/AAS projects

AERA 3 [NFC+83, Nie89b, Nie89a] is a fully automated control system project, whose concept is studied by the MITRE corporation, sponsored by the FAA. In AERA 3, the automated system assumes for the first time, responsibility for separating aircrafts, whereas AERA 1 and AERA 2 left this responsibility to the controller. However, AERA 3 must be seen as the continuation of AERA 1 and AERA 2 and this may explain its structure. In AERA 3, short term, medium term and long term planning are represented by three nested shells. The innermost shell, called Automated Separation Function (ASF), only resolves pairwise separation problems, considering them one at a time. ASF only looks a few minutes in the future (not more than five minutes). The next shell out, the Maneuver Option Manager (MOM), considers interrelated pairwise separation problems (called clusters) among sets of aircrafts. It determines a set of maneuvers (called outs) whereby such interrelated possible problems are simplified into pairwise possible problems, (called possiblems). MOM looks about 30 minutes in the future. The outermost shell is known as the Airspace Manager planning functions, whose lookahead period is about 90 minutes. It is the only task partly left to the controller, who would become an airspace manager. This shell consists of automation aids to prevent traffic from becoming too dense for MOM to handle.

The AERA 3 project was a full automation project. The AERA 2, and AAS[9] projects are slightly different. The idea there is to provide the controller with direct resolution solutions, the controller being still in charge of the decision to let the machine implement the proposed resolution or to change this resolution to give himself his own resolution.

The transition from AERA-2 to AERA-3 is quite clear: the controller in AERA-2 is almost only a supervisor, and in AERA-3 he will become only a supervisor in charge of monitoring the behavior of the system and of taking strategic decisions, in terms, for example, of flow management.

The drawbacks are well known and the main risk is the following: the controller will rely more and more blindly upon the machine and will then almost automatically validate computer solutions without double-checking. Moreover, in case of system failure, he might not be able to take charge again of the control system.

[9] Advanced Automation System

3.4 Dynamic task sharing (SPECTRA)

The SPECTRA[10] approach is the following: the principle is to share tasks between the computer resolution program and the human operator ([Pla93]). The main idea is to let the operator in charge as long as workload in the sector is not too large. As soon as workload reaches a given level, the computer will automatically take charge of "simple conflicts", leaving to the human operator the resolution of difficult problems.

In a transition phase, this technic has many advantages. In the beginning, if the program is only able to handle very simple problems, the controller can still solve the remaining ones. As soon as the program becomes better for conflict resolution, it will solve more and more problems in a gradual, progressive way. This is definitely an excellent approach to have a smooth transition from a control system completely managed by a human operator and a control system where the computer is almost completely in charge. Moreover, the human operator will still have problems to solve in under-loaded period, and will then be able to maintain his qualification.

The SPECTRA system, apart from specific experiments has been integrated in one of the scenarios evaluated during the SWIFT project which aims at defining the future controller working position ([Duj93a]).

Of course, there are always drawbacks even in this approach. The main risk is the automatic allocation of the resolution of some conflicts to the computer. Even if the human operator is aware of the allocation, he might forget that some planes will be moved, or forget how they will be moved and how it might interfere with the resolutions he has to perform.

However, this is definitely one of the most promising technics to complete a correct and smooth transition.

4 How to achieve the objective?

4.1 Technical considerations on intermediate steps

There are lot of technical problems that must be solved to make the step from nowadays systems to fully automated systems. We can quickly list some of them:

- All planes should be fitted with precise devices enabling them to follow definite trajectories, in 4 dimensions.
- All planes positions have to be very precisely known, whether with enhanced radar systems, GPS, or other similar systems.

[10] Système de Partage des tâches Expérimental pour le Contrôle du TRafic Aérien

- For an optimal security, all planes should used ACAS/TCAS systems.
- etc...

Of course, this list is definitely not exhaustive. There is especially one very interesting point to discuss: how can we technically design a system that would smoothly go from a human centered system to a “computer centered system”? An interesting approach would be to design tools for the controller that could evolve into an automated systems. For example, let's take the ARC2000[11] resolution method, called by its designer the rubber band method. Each plane already accepted in the system has a trajectory represented in a 4D space by a cylinder or a conical volume. When a new plane is taken into account, its trajectory can be considered as a rubber band that must be tangent to each cone that it has to cross.

Instead of directly sending the computed trajectory to the plane, it can be displayed to the controller, who can decide to modify it in the space of constraints which can be displayed as cones. Such graphical tools are being investigated by Eurocontrol in its ODID IV project.

4.2 Transition and human factors

4.2.1 The limits of the Human-Centered approach

The classical definition of the human centered approach is: **the system must provide information to the human operator who will then make the resolutions and take the decisions.** This kind of system is usually opposed to systems which solve the problems and provide directly solutions to the operator. But then, where is the limit between aiding tools and problem solvers? When is the operator no more able to build a solution by himself and rely completely on the information provided by the system? When is the operator objectively *in* or *out* the decision loop? The point is not to say that the operator is still in the decision loop but to be able to verify that he is really in charge.

The main characteristic of this approach is its step by step way of evolution. This evolutionary method is a guaranty of the acceptance by the users of the system. On the other hand we must consider its weakness in identifying of a long term goal and its rather poor appreciation of what will be the performance and/or limits of such a system in the medium and long term.

4.2.2 The involvement of the future users in the design process

It is nowadays a common process to involve the users in the design and evaluation phases [Duj93b]. However some questions must be raised for they tackle non trivial problems, especially in the ATM field :

- Who are the real users of the system the designers have to consider? Are they the air traffic controllers? the pilots? the airliners? or the air passengers? Depending on the answer chosen, the criteria to take into account can be different.
- Do we speak of "future users" or of users of a "future system"? This question highlight the major concern about training and transition.
- Users generally have difficulties in conceiving solutions drastically different from the present ones; therefore the way to involve them in what remains a "system engineer" process must be rethought about.
- In the past few years, cognitive engineering has appeared to be the best way to design system evolutions with limited transition problems, even if the appropriation of a system by the operators remains difficult to anticipate. If the new system can no more be considered as a mere evolution but when there is a real gap, no cognitive model can be used and this approach is no more relevant. A different approach has to be considered.
- What allows today a new ATC system to be used is not validation, even less certification; in the best case expert opinion combined with user acceptance is considered as an implicit validation. The problem can be solved only because there is no difference in the human-system task sharing between the different systems is unchanged. When this human-system task sharing is to be modified, an actual validation methodology has to be defined [Hop93].

4.2.3 Human-human communication and task sharing

It has been demonstrated that human operator performances are higher than system ones in some tasks, system being much better in performing other ones. In the ATM where several operators are involved: executive and planning controllers of one sector, controllers of the different sectors (where this organization exists) and pilots. It is therefore essential to consider that automation, whatever the path followed to implement it, will cause big changes in the tasks to be performed and in the repartition of roles among these different actors: strategic vs tactical control, air vs ground responsibility.

4.2.4 Transition

It is well known that partial automation of some processes can induce new possibilities of human errors, by increasing the underlying complexity of the task of the operator. So, the road leading to a more automated system while keeping the man in the control loop, with an increased reliability, is narrow and difficult.

[11] Automatic en-Route Control

We have also discussed a dynamic allocation of tasks between the human operator and the computer, given the current workload, and other parameters. This approach has to prove that it is possible to correctly allocate tasks. If so it can be considered as the most attractive transition path

5 Conclusion

The point we wanted to stress in this paper is the following one: each transition alternative can be view as a cursor on a linear scale going from "easy to accept today, making a transition to automation almost impossible" to "difficult to accept, good way to automation". Choosing one of them is mainly a political problem. However, the problems left unanswered today will still be there, and much more acute, tomorrow.

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