Challenges from the Introduction of Artificial Intelligence in the European Air Traffic Management System

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Abstract: The Air Traffic Management (ATM) system can be defined as a "Joint Cognitive System" of people, teams, and artifacts that adapts to the challenges and demands posed by familiar and unfamiliar situations in a dynamically evolving operational context. In the era of digitalization and Big Data we live, an incremental modernization of the ATM system is expected in the coming years with the pervasive implementation of Artificial Intelligence (AI) and Machine Learning (ML). In this paper, we present the findings from an initial attempt to detect and document the fundamental challenges of the introduction of AI, in the European ATM system through the lens of Cognitive Systems Engineering paradigm. We also discuss how these challenges give rise to difficult to resolve safety and performance related patterns in the ATM system.

Keywords: Cognitive Systems Engineering, Joint Cognitive Systems, Air Traffic Control, Air Traffic Management, Artificial Intelligence, Machine Learning, Digitalization.

1. INTRODUCTION

It is widely accepted that a pilot in a cockpit is one of the earliest and most enduring symbols of what we can achieve with a positive and collaborative working relationship between humans and machines. If we make a step further and consider as the unit of analysis the airplane, i.e., the pilots plus flight control and automation, as the flight Joint Cognitive System (JCS) then the Air Traffic Management (ATM) is the environment. It is also possible to go one more step further and consider the pilots and the ATM as one system—the traffic flow JCS (Figure 1)—in which case the environment is the airlines, the airports, and the other aviation stakeholders (Hollnagel, 2007). In the era of digitalization and Big Data, this traffic flow JCS faces important and potentially disruptive challenges with the introduction of Artificial Intelligence (AI) both in the air and the in the ground components. It is ubiquitous that the use of AI is spreading rapidly in every industry with aviation and ATM making no exception.
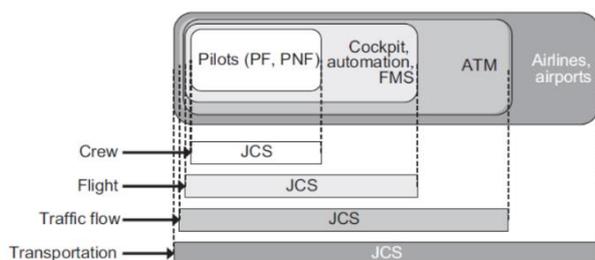

Figure 1. The traffic flow Joint Cognitive System (Hollnagel, 2007).

However, innovative technologies not only provide capacity enhancement opportunities and other performance improvements but also raise new regulatory, safety, cognitive and operational challenges, and tradeoffs. Therefore, there is an urgent need to examine the introduction of AI cautiously. In this paper, we present an initial attempt to detect and document the fundamental challenges of implementing AI, in the European ATM system through the lens of Cognitive Systems Engineering (CSE) paradigm (Hollnagel and Woods, 2005; Woods and Hollnagel, 2006).

1.1 Motivation

The significant and continued growth in air traffic in the years prior to the COVID-19 pandemic has prompted considerable exploration of the use of AI in the ATM. It is expected that AI will provide the additional capacity to meet the challenges of increasing air traffic complexity due to sustained growth and new airspace users and support more efficient and environmentally friendly operations while maintaining and increasing current safety levels. Modern ATM systems comprise many airspace sectors with varying air traffic flows that interact in complex ways and evolve dynamically. ATM is a work domain that relies on the cognitive functions of Air Traffic Controllers (ATCOs) and their collaboration with flight crews, airport operators, network managers and the other aviation stakeholders to control the airspace, manage safety and adapt to the changing demands of new technological initiatives (Kontogiannis and Malakis, 2017). According to EASA (2021) while the concept of AI has been in existence since the 1950s, its development has significantly accelerated in the last decade due to three factors: a) significant improvements in the capacity to collect and store massive amounts of data (i.e., Big Data), b) significant increases in computing power and c) development of powerful algorithms

and methods. From a purely AI view the ATM system is a real-time safety-critical decision-making process in highly dynamic and stochastic environments where human air traffic controllers monitor and direct many aircraft flying through its designated airspace sectors (Brittain et al, 2020). The extensive introduction of AI is expected to create a new ATM environment which will be tightly coupled, more complex to cope, with increased air traffic, and pressing needs for a) minimization of delays, b) accommodating a diverse array of autonomous aircraft, c) operating in adverse weather, d) smoothing out 4D aircraft trajectories and e) minimizing environmental impact. AI is expected to increase the resilience and the flexibility of the system (i.e., increase support during emergency in flight or on the ground or unusual situations, as severe weather, failures etc.) and to increase the situational awareness of the operators (e.g., ATCOs and Pilots). In parallel ongoing EASA's projects such as Extended Minimum Crew Operations (eMCOs) and Single Pilot Operations (SiPOs) rely heavily on AI and the application of powerful Machine Learning (ML) methods. eMCOs are defined as operations where the flight time is extended by means of rest in flight with the minimum flight crew. It is achieved by allowing operations with one pilot at the controls, during the cruise flight phase; however, offering an equivalent overall level of safety through compensation means (e.g., ground assistance, advanced cockpit design with workload alleviation means, pilot incapacitation detection). SiPOs are defined as end-to-end single-pilot operations. Air operations regulation already foresees conditions and limitations under which these types of operations are allowed. In the future, it is expected that these conditions and limitations will need to evolve to extend single-pilot operations to large airplanes, provided that compensation means (e.g., ground assistance, advanced cockpit design with workload alleviation means, capability to cope with pilot incapacitation) are in place in order to provide for an overall level of safety equivalent to today's two-pilot operations. EASA is working with interested industry stakeholders to explore the feasibility of such operational concepts, while maintaining current safety levels. It is evident that both projects that rely heavily on AI and ML will need ATM support and therefore introduce new operational requirements for the ATC. All these will impose a brand-new array of challenges to the ATM systems in the next 10 to 15 years. In this context we attempted to elicit and document fundamental challenges to the ATM system from the introduction of AI with of the view of drawing the attention to the potential side effects that we must act upon promptly.

2. METHODOLOGY

We used a range of methods over several phases of fieldwork, documentation analysis and finally divergent thinking, comparative reasoning, and integrative thinking to compile the final list.

In the fieldwork phase, we used many methods. These ranged from participation in structured group discussions (e.g., concerning AI certification) and in-depth discussions (e.g., AI related projects). From a Cognitive Systems Engineering (CSE) perspective, these techniques belong to the 'natural history' family of methods that are based on a diverse

collection of observations in situ (Hoffman and Militello, 2009). This was a recurrent step that was used throughout the whole process. The result of each round was an improved version of the list of fundamental challenges. The next step was to consolidate the list by performing a documentation analysis. During this step we applied a documentation analysis of the most recent reports, white papers, position papers and technical documents from ATM and aviation organizations (EASA, 2020, 2021; EUROCONTROL, 2021a, 2021b; CANSO, 2021, 2021) regarding digitalization and AI in the European continent. The next step was to perform a literature review. There is an extensive body of high-quality research in the human factors and CSE literature that can inform the development and application of automated systems which is beyond the scope of this paper. Therefore, we decided to concentrate on some influential research publications and reports in the areas of automation AI, CSE and ATM (Bainbridge, 1983; Parasuraman and Riley,1997; Dekker and Woods, 1999; Moray and Inagaki, 1999; Parasuraman et al. 2000; Russell et al 2010, Woods and Sarter, 2000; Woods and Branlat, 2010; Woods et al, 2010; Norman, 2013). We also reviewed similar research efforts (Prevot et al. 2012), acceptance of automation studies (Westin, et al. 2016) and introduction of ML techniques can be used in developing classification rules and eliciting knowledge in the area ATM system (Malakis et al. 2020). Finally, we applied divergent thinking, comparative reasoning, operational expertise, and integrative thinking by capitalizing on the knowledge and operational expertise of the team members through successive rounds of drafting, commenting, and finalizing the list.

In compiling the final list of fundamental challenges, we followed the next principles:

Fundamental challenges should not be overlapping. To this end we performed a vertical division into five widely accepted levels in the ATM system, which were identified through the literature review. These levels are: 1) Political / Regulatory. 2) Air Navigation Service Providers (ANSPs). / Business. 3) Technical. 4) Operational. 5) ATCOs.

Fundamental challenges should not be contradictory. This is a critical requirement as a challenge in one level may be neutral or even beneficial in another especially between Political / Regulatory which is the highest level of abstraction and all the other levels.

Independent of the size, complexity, staffing levels and nature of operations of the ANSPs to which they apply. It is widely accepted that the ATM provision in the European Contingent is fragmented (Finger et al., 2014; Andribet et al., 2022). Therefore, compiling the list having in mind only one or two ANSPs will certainly distort and bias the analysis. To avoid this, we selected only those challenges that are common for the majority of the European ANSPs.

Address the European ATM although most of them can be applied to other ATM systems worldwide. European ATM is a unique blend of increased traffic levels, capacity shortfalls, ANSPs fragmentation and complexity among all the worldwide ATM systems. The US ATM system for comparison has an extensive degree of cohesion in terms of

ATM provision, CNS systems used, training of ATCOs and centralized oversight. Therefore, we focused only on the European ATM system although quite a few of the challenges may also be valid in other ATM systems worldwide subject to more research.

Pragmatic in nature. Given the diversity of AI related projects there is always the risk that superficial, inconsequential, close to maturity or even remote challenges to be identified. To avoid this trap, we focused only on pragmatic challenges that were uniformly identified and well understood in nature.

Not connected to a particular AI paradigm and ML method to the extent possible. There is plethora of methods, tools, paradigms, and application with regard of AI and ML (Russell et al 2010, Barredo Arrieta, 2020). Focusing on a particular method, tool or application would have resulted in a narrow and potentially outdated analysis. For instance, there is a growing literature on the explainability issues of AI (Barredo Arrieta, 2020). Especially for Neural Networks which is the state of the art in Deep Learning. However, focusing only Neural Networks would have restricted our scope into a particular paradigm and method.

3. RESULTS

The fundamental challenges from the introduction of AI in the European ATM system are outlined below.

3.1 Political / Regulatory

The challenges in the Political / Regulatory area are the following:

- Fragmentation of the European ATM sector (Finger et al., 2014; Andribet et al., 2022).

- Complexity and novelty of AI related products certification.

- Obsolescence of traditional development assurance frameworks that are not adapted to ML and development of the Learning Assurance Concept (EASA, 2021).

- State sovereignty concerns.

- Legal differentiation between Air Traffic Services Providers and ATM Data Service Providers.

- Geographical redundancy and availability of ATM data centers.

- Complexity of agreements on risk sharing and charging mechanism between States.

- Definition, sharing, and applying a common policy on ethics, related to AI.

- Maintain the credibility and reliability of the ATM systems by promoting social acceptability and change management.

- Build the trust of operators through a system of rules that distribute and clearly define the responsibilities and operating limits of the AI and the operator.

3.2 ANSP / Business

The challenges in the ANSP / Business area are the following:

- Organizational transformation issues.

- Insurance and liabilities.

- Constraints from the early adoption of new technology.

- Unclear cost-effectiveness benefits.

- Complexity of service borders and scope definition.

- Costly reinforced cybersecurity infrastructure.

- Complexity of service continuity requirements.

- Disruption of established knowledge sharing, learning procedures, and practices within ANSPs.

- Encourage simulation, training, and feedback paths from operators, to be shared with systems developers.

- Build a new change management policy to gradually drive operators through new technologies and working methods.

3.3 Technical

The challenges in the technical area are the following:

- Complexity of sharing of AI infrastructure between countries.

- Extreme dependency of the ML models on the datasets that are used for training, validation, and testing.

- Curse of dimensionality, which refers to the extraordinarily rapid growth of the complexity, as the number of variables (or dimensions) increases (Bellman, 1957).

- Significant differentiation of AI solutions for Tower, Approach and Area Control operations.

- Tailor made AI solutions for each use case that cannot be easily generalize across same type of units in different geographical areas.

- Consolidation of critical data to guarantee consistency, integrity, and safety of displayed information on the Controllers' Working Positions.

- Develop backup systems to face failures or unusual situations in complex AI systems.

- Define effective AI methods to detect, frame into context, and interpret into decisions weak signals.

3.4 Operational

The challenges in this area are the following:

- A scale shift in complexity in terms of the density of interdependencies across processes and activities.

- Synchronization of operational procedures between Air Traffic Services Units (ATSUs) and between ATSUs and Network Manager.

- Incompatibility with existing Concept of Operations (CONOPS) and the need of development of new ones.

- Explainability issues of the ML models.

- Function allocation issues. Avoiding leftover strategy where the ATCOs are expected to assume control when automation fails.

- Develop, validate and harmonize the integration of AI technologies in the whole system, among all users (ATCOs, pilots, aerodrome operators and Network Manager).

- Disruption of established relationships, lines of communication and the ability to exert authority.

3.5 ATCOs

The challenges in this area are the following:

- Keeping the ATCO 'in the loop' and situationally aware and able to intervene.

- Disruption of established patterns in coordinated activity between ATCOs' and between ATCOs' and flight crews.

- Disruption of established patterns of resilience.

- Increasing instances of automation surprises and clumsiness.

- Increased space for potential and new type of errors that cannot be easily foreseen.

- Demands for new kind of knowledge and skills.

- Demands for more threads to track that makes attention management difficult.

- Demand for the development of new mental models, how the AI system works, how it fails, why it fails, and how to adapt (Borders et al, 2019).

- ATCOs acceptance of their new roles and remits.

- Synchronizing an increased number of micro-cultures of ATCOs' communities which are based on their local practices and local affordances.

- De-Skilling of ATCOs.

- ATCOs' intervening during failures and contingencies, (Leftover strategies).

- Vigilance / boredom tradeoffs.

- Managing of social aspects (e.g., relocation and mobility of ATCOs).

- Resistance from ATCOs' who could legitimately fear for their jobs.

4. DISCUSSION

Although the pandemic of Covid-19 significantly decreased the number of flights by slowing down the air transportation system in 2020 and 2021, this is not going to be a permanent situation. Commercial aviation already (June 2022) shows signs of a significant rebounce. The ATM systems is operating on its usual high traffic levels and the need from the introduction of AI in the ATM will gain momentum. AI is promising costs reduction, flight efficiency, improved strategic planning, enhanced trajectory prediction, and fuel efficiency to name but a few. However, it is evident from the challenges above that many and difficult to tackle challenges emerge. The range of challenges that were identified previously may well be the enablers of following safety and performance related patterns.

4.1 Difficult organizational and operational trade-offs

Operations rooms are hectic workplaces, and in many cases, work demands exceed resources, so ATCOs have to do their best and manage their traffic by adjusting their practices to meet existing conditions. In this sense, they are trying to maintain a continuous balance between demands and resources. Moreover, this does not only concern high workload situations, but also low workload periods, during which ATCOs need to maintain their performance and awareness levels despite not having enough to do to keep them engaged. The effort to tailor human performance to work demands can be described as if it involved a trade-off between efficiency and thoroughness. This view has received particular emphasis from Hollnagel's (2009) proposition of the Efficiency-Thoroughness Trade-Off (ETTO) principle. To cater for efficiency, ATCOs generally try to achieve their goals by keeping their efforts and resources (for example workload) as low as possible. Safety, on the other hand, requires that more resources are spent on ensuring that the necessary conditions are in place, so that performance goals are achieved without risks. Safety implies that ATCOs spent more time in thinking whether preconditions for an activity are met, execution conditions are right and preparations for contingencies are made in advance. ATCOs have to reach both their safety and performance goals, neither of which should be achieved at the expense of others. In this line of reasoning unresolved challenges from AI projects will most certainly disrupt this fragile balance and create room for new and more complex dilemmas. Additionally, very thorough investigation will be required to determine how many, and which ATCO tasks will AI take over and/or assist with. For example, completing the simple and routine tasks would be beneficial in a high workload situation, as this would allow ATCOs to focus on the complex tasks, but detrimental in a low workload situation, as

it would even furthermore reduce ATCOs engagement and could lead to reduced situational awareness and performance levels.

4.2 Difficult organizational and operational trade-offs

Current safety methodologies cannot cope well with AI related projects especially when it comes to learning assurance (EASA, 2020, 2021). EASA developed a multiyear project to address exactly this type of weakness in certification. ANSPs' safety methodologies focus on the needs of single agents, but do not allow risks of different types and sources to be assessed with reference to each other, singly or in combination in dynamic environments. Hence, dysfunctional interactions arise that are beyond the control of single agents and current methodologies cannot adequately deal with them.

4.3 Transform or transfer hazards to other stakeholders

In many cases, risks may be transformed or transferred among ATM stakeholders since the solution of one's own concerns may create problems elsewhere. For instance, adverse weather is a safety hazard for all flight operations. When weather cells are encountered, flight crews may request to circumnavigate cells which could increase traffic complexity for ATCOs particularly in congested airspaces. Hence, granting a cell circumvention to aircrews may increase the risk of separation minimum infringement and reduce the margin of maneuver for controllers. On the contrary, flight operation hazards are effectively reduced. The increase in air traffic complexity (e.g., more conflicts points) as several air crews are requiring changes to their routes to circumvent the weather cell cannot always be mitigated by ATFCM restrictions alone. Corver and Grote (2016) showed that area controllers, in addition to reducing and acknowledging uncertainty, may deliberately increase uncertainty to increase flexibility for other actors in the system to meet their operational goals. On severe weather days, ATCOs often forgo a few procedures, e.g., coordination requirements, to increase their overall efficiency in handling the complex traffic and to ensure the safety of the aircraft. These results are particularly important as uncertainty is likely to increase in future AI supported operations of area control ATC especially since explainability issues will remain an issue (Barredo Arrieta, 2020). Therefore, risk transferability between ATM stakeholders which is common now and, in a sense, understood (because work practices are built upon it) will most probably be disrupted with unwanted safety and performance consequences. For this reason, any AI that is introduced in ATC has to be modeled in a way that matches the ATCO working practice and culture.

4.4 Patterns of events that are difficult to anticipate, monitor or comprehend

Complex aviation systems require pilots and controllers to anticipate critical events and stay ahead of traffic so that they get prepared for new evolving situations. For this reason, the set capacity values for a specific sector are often lower than the actual capacity. In fact, many automated support tools have been designed to allow practitioners to foresee the evolution of weather and traffic, which then gives information on whether a sector would become overloaded and whether the gap between set capacity value and actual capacity will be filled.

Anticipation of evolving traffic becomes very important since traffic patterns may be affected by factors controlled by different ATM stakeholders (e.g., airlines, airports and ANSPs). With the introduction of AI in the air and on the ground new patterns of events that are difficult to anticipate, monitor or comprehend will materialize. In addition to preparing and updating the currently existing contingency plans, consideration will also have to be made towards potential AI-related issues. This will certainly entail implications for the safety, performance, and capacity of the ATM system.

5. CONCLUSION

There are a lot of questions to be answered in those five levels we identified, with the most critical being at the ATCOs level. In this context IFATCA has created the concept of Joint Cognitive Human Machine System (JCHMS) or a Human Centric approach and wishes to influence ICAO and standardization bodies such as EUROCAE and EASA in Europe as well as other global organization such as RTCA, SAE in the way these new technologies are designed. This is a first step towards this goal of raising awareness to challenged raised by the introduction of AI in the European ATM system. It is widely accepted that each technology shift—as the wide scale introduction of AI in the ATM —extends the range of potential control. In doing so it also extends the range of potential control of the JCS that performs the work as well. Woods and Branlat (2010) framed these challenges in the form of two simple questions: What does it now mean to be 'in control'? How to amplify control within the new range of possibilities. We argue that the way forward in answering the challenges that we have documented above includes the provision of definitive answers to these questions.

5. DIRECTIONS FOR FURURE RESEARCH

The findings of this study are pending further validation and generalization due to the exploratory character of the research. However, many of the challenges drawn from this study are expected to remain relatively stable when additional studies are carried out. Errors introduced by designers in developing AI systems can themselves be major source of safety and operational problems in the ATM. In our view a) many studies must be designed that take into account the challenges we identified and b) aircraft operations related projects such as eMCOs and SiPOs ought to include the prospect of collaborating with an AI assisted ATM system.

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