Current Developments and Challenges in Civil Aviation Automation and Solutions to Address Them in the Future

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Abstract. Aviation autonomy has advanced rapidly. Nevertheless, most civil aviation aircrafts still fall into the category of level-3 or level-4 automation, far from the goal of level-5 complete autonomy. With newly developed automation systems like the CAPS and the implementation of AutoSOAR systems and the NASA TASAR project, they will be a leap forward in automation technology in the near future. Nevertheless, there are also many technical and regulatory challenges: technically, problems of unreliable sensors, complex system integration, and the difficulty of verifying artificial intelligence for safety-critical decisions occur; regulatorily, distrust in reliability and outdated regulations in the regime of flight automation occur. They are all restricting the development and application of such automation systems. That being said, more mature automation systems and more robust safety and reliability tests must take place, along with the introduction of guidance documents from authorities to fully address the challenges. It is believed that with more reliability tests and developments and proper guidance documents, flight automation systems will take a lead forward and benefit the aviation industry.

1 Introduction

Since the beginning of the development of commercial aviation during the first half of the 20th century, the pursuit of mechanical autonomy among aircraft has never stopped. Anderson et. al have emphasized that the definition of automation in road vehicles is "the real-time operational and tactical functions required to operate a vehicle in on-road traffic," and therefore connected this definition to the level of automation in the field of aviation [1]. In the air, the pilot must control the aircraft in the third axis of control (altitude), one more axis of control compared to cars, and planes cannot be simply stopped when problems occur. Thus, aircraft automation is a much more complex task than vehicle automation, and considering that commercial aircraft usually carry hundreds of passengers onboard, the reliability and safety of such automation systems need to be justified.

Automation in aircraft has developed greatly in recent years, including autopilot, auto landing, and auto braking systems etc. Nevertheless, a more autonomous system onboard aircraft has been the goal for engineers. A highly automated system will reduce pilots'

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workload and mental pressure while increasing control efficiency [2]. That being said, the flight must maintain a minimum number of pilots and workload as required by the Federal Aviation Administration of the US, and prioritize the pilots' decisions during the whole flight [3]. Thus, the further development of automation needs to follow the requirement, or otherwise challenge the regulations for a change.

Taken together, promoting autonomy has the benefit of lower mistake rates, lower workloads for air crews, and higher efficiency and accessibility in the air. Nevertheless, there are currently many technical limitations in the development of aviation automation, and the major administrative bodies have yet to keep up with regulatory edits that will ensure the sustainable development of such technology.

2 Current civil aviation automations

2.1 Levels of aviate task autonomy

Defined as "aviate tasks", the highest priority for pilots includes keeping control of the aircraft and avoiding obstacles and accidents. Pilots are required to possess a thorough understanding of the aircraft and its limits, as well as good observation of the environment. Automation systems, therefore, must assist the pilot in performing such aviate tasks: in particular, flight path planning and control, and collision and obstacle avoidance [1].

Table 1 shows the levels of aviate task autonomy, which can also be seen as the levels of flight autonomy in general.

Table 1. Levels of aviate task autonomy

Aviate Tasks					
Level	Name	Description	Path Control	Obstacle Aviodance	Fallback
0	No Automation	Pilot controls all aspects	Pilot	Pilot	Pilot
1	Assistance	Limited, specific system assistance in aviate tasks	Both	Pilot	Pilot
2	Partial Automation	≥1 portion of task being system-controlled	Both	Pilot	Pilot
3	Highly Automated	Most aspects of aviate task being system-controlled	Both	Both	Pilot
4	Fully Automated	All aspects of aviate task being system-controlled under most conditions	System	System	System
5	Autonomy	All aspects of aviate task being system-controlled under all conditions	System	System	System

Most of the current civil aircraft are equipped with level 3-4 automation systems. As the different levels of flight autonomy are being clarified in the table above, the further development of aircraft automation can follow the categorization as a guidance rubric and make further automation possible. Moreover, limitations in technology and regulations can be more easily discovered when using the rubric for development.

2.2 Levels of automation in non-aviate tasks

Aviate Tasks are the tasks with the highest priority among pilots. Apart from aviate tasks, the pilots are also required to perform many other tasks, including navigation tasks, which are the second most prioritized tasks that determine the location of the aircraft and its designated direction of travel; communication tasks, the third priority that maintains situation awareness and responds to instructions through communication with Air Traffic Control (ATC). In addition, system management tasks and command decision tasks, usually underestimated in importance, are also among the critical tasks pilots perform. They are the operation and oversight of the flight system and the decision to perform any operation choices that affect the plane, respectively [1].

The levels of automation among all the mentioned, less prioritized tasks above are also categorized into 5 types, just like the categories in Table 1. The contents are similar as well, with the same corresponding fallback and task performance characters (pilot or system, or both). Most modern-day commercial aircraft all fall into the category of level 3 of the automation level, which shows the direction of future developments is to march towards complete level 4, and mostly level 5 automation among commercial aircraft.

3 Current developments and innovations in automation systems

3.1 The cockpit automation procedures system

Current commercial aircraft flight decks include the Electronic Centralized Aircraft Monitor (ECAM) and Engine-Indicating and Crew Alerting System (ELCAS). Both systems are used to alert pilots of ongoing or potential system/ mechanical failures and provide procedures to instruct pilots to eliminate the problem. These systems fall into category 3 of automation according to Table 1. However, the drawback of both systems is that the final decision is to be made by the pilot, while the system only provides procedures for the crew. In case of aircrew disability and unexpected accidents, the response efficiency and effectiveness towards problems will be low [2].

To address the mentioned drawback, Alvarez et.al introduced the Cockpit Automation Procedures System (CAPS). The CAPS aims to promote autonomous system management by controlling the aircraft through a unique interface. The CAPS can also be authorized a varying degree of authority and make decisions regardless of the flight crew's involvement in the decision loop [2].

According to the researchers, the CAPS's goal is to achieve complete automation in the future, with several steps in front of the current CAPS scope. The current scope of CAPS lies in the first, and fundamental phase, which is based on data collection and procedures automation, restricted to current automation regulations. The next phase is the development of an algorithm that aims at decision-making. In collaboration with the CAPS, the algorithm will grant a higher level of automation under pilot control. This stage of automation is not granted by current regulations. The third phase is decision-making algorithm control under pilot monitor, not control, and at last, complete autonomy. These development phases are illustrated in Figure 1.

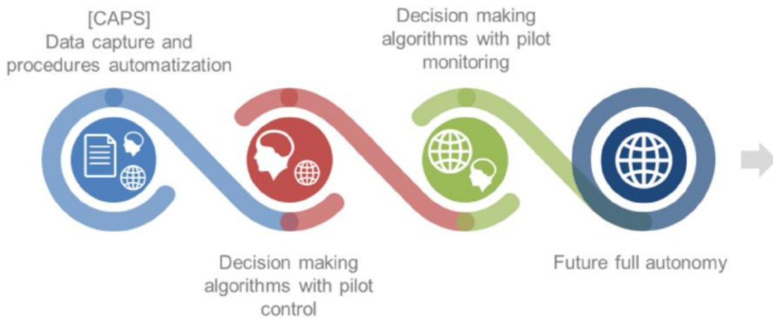

Fig. 1. Aircraft Autonomy's Developmental Roadmap [2]

The CAPS is defined as a system to automate cockpit procedures, mainly procedures under abnormal scenarios. The CAPS do not replace the aircraft's warning system and requires an internal database of emergency procedures and actions onboard the aircraft.

3.2 POMDP-Based autonomous aircraft trajectory planner

The autonomous aircraft navigation system has been one of the most important aspects of plane autonomy that has been longing for a novel development approach. A brand-new controller has been developed by Trotti et. al to control the trajectory of aircraft during flight under uncertain conditions. By providing optimal commands to arrive at the destination while also avoiding no-fly zones, the system is a state-of-the-art approach to autonomous aircraft navigation [4]. The control system is also able to consider various performance aspects of the aircraft (e.g., fuel consumption and travel distance) while planning the route.

Specifically, the system used a two-layer decision-making controller. A Partially Observable Markov Decision Process (POMDP) is the outer loop, as well as the high-level controller in the decision process. An inverse dynamics controller acts as the inner loop, the low-level controller in the process. The decision process involves the POMDP providing accurate values and reference to the inverse dynamic controller (inner-loop), then the inner loop controller controls the aircraft's actuators to maneuver it according to the needs of the crew, and reach the destination.

The system was tested under a simulation scenario and reached the destination successfully. The POMDP has shown to have the ability to calculate and generate accurate values for the inverse dynamic controller, marking the success of the first stage of development in this navigation system [4].

3.3 The autosoar algorithm system in the context of civil aviation

Since the first introduction of autonomous soaring in detailed simulations in 1998 [5], the topic has been widely studied for decades. One of the latest innovations in the field is the Autonomous Sailplane for Atmospheric Research (AutoSOAR) system by Depenbusch et. Al [6]. The system is a set of autonomous soaring algorithms that addresses the following tasks:

(1) Energy state estimation and mapping of energy sources in the environment.
(2) Control and guidance of flight based on the wind map and on the lift feature map.
(3) Algorithms for exploration based on the atmospheric map and on heuristic predictions based on terrain, solar incidence, and ground cover.

Figure 2 below shows the decision-making process of the AutoSOAR system, in which the autopilot provides sensor information to the onboard computer that runs the soaring system. The autopilot is also able to control the aircraft's actuators in low-level control.

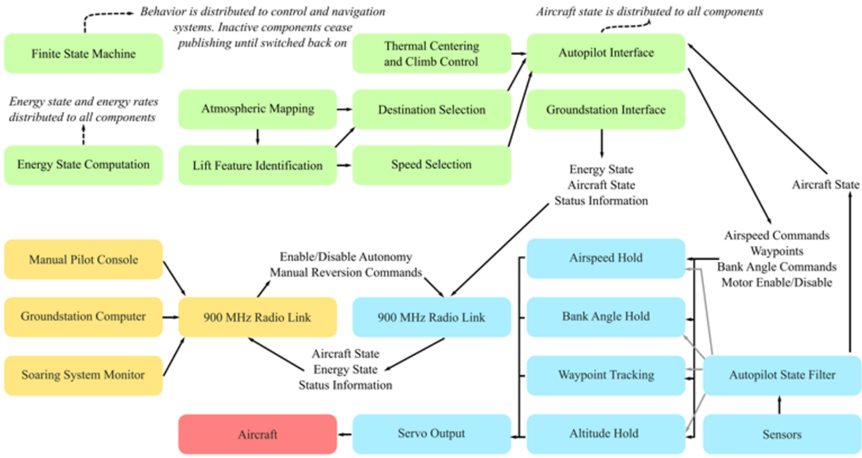

Fig. 2. The AutoSOAR System's Decision-making Algorithm

The AutoSOAR system is meant to operate onboard small, unmanned aerial vehicles (UAVs) that perform autonomous atmospheric exploration missions. Nevertheless, the algorithm and technology of automation can also be implemented onboard larger, manned civil aviation aircraft to a certain extent.

The automation level of the system is of a different category and logic compared to commercial aircraft, since the AutoSOAR is onboard UAVs. As mentioned previously, the decision-making process of the system involves the low-level control of the autopilot according to atmospheric and terrestrial conditions. Thus, the system, though it cannot be used as the primary automation system onboard commercial aircraft, can serve as a secondary automatic control system under abnormal situations like engine failure or primary automation system failure. Moreover, the auto adjustment of the AutoSOAR system can potentially be very helpful under powerless conditions, since it was originally developed for soaring aircraft with low or no power output.

3.4 The TASAR system in flight route optimization

The Traffic Aware Strategic Aircrew Request (TASAR) concept is a newly developed approach to promote flight autonomy by NASA. The system is aimed at advising the pilot for route changes that would be beneficial: either for flight economics or avoidance of severe weather [7]. The TASAR introduces a brand-new, powerful ability for aircraft trajectory management during flight by connecting to the onboard computing systems and avionics systems to ensure a continuous, reliable data stream for the TASAR algorithm.

With the development in the aviation industry, the role of pilots is also changing. With the assistance of the TASAR system, pilots are no longer simple followers of pre-planned flight paths, but proactive flight trajectory controllers. This is a critical step in the initial march towards complete level-5 flight automation (complete autonomy), as current trajectory planning lacks the active involvement of algorithm systems in advising the pilots of optimal flight paths [7].

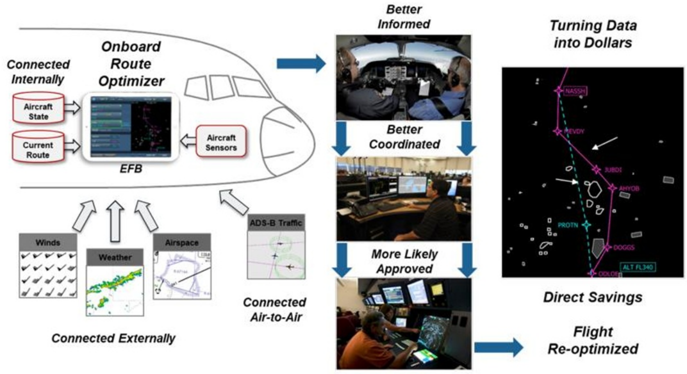

Fig. 3. The TASAR concept

Shown above in Figure 3, the TASAR is considered more of a catalyst for operational autonomy on board aircrafts; it should be combined with other low-level control systems or in collaboration with other high-level automation systems to fully bolster the automation level of commercial aircrafts. This is a unique characteristic of the TASAR system that separates it from the previously introduced automation systems. Working with pilots, the TASAR system, once completed, will fulfil NASA's vision towards full aviation autonomy, dating from decades ago [7].

4. Current technical and regulatory challenges encountered

4.1 Technical challenges and feasible solutions

4.1.1 Sensor unreliability

One of the most concerning technical limitations towards full aircraft autonomy is the reliability of the autonomous operating systems. Both automation systems and pilots rely on the numerous sensors onboard to make decisions. But sensors can fail subtly through biased data, noise, or spoofing [8]. Faulty sensor inputs will often lead to faulty decisions, which could lead to devastating results. This can be illustrated by the Air France Flight 447 disaster, which crashed into the Atlantic in 2009, due to a failure of the Pito Tube (a sensor that detects the airspeed of the plane), killing all passengers onboard [9].

Thus, in these cases of sensor failure, the primary sensor data should first be compared to redundant sensor outputs for cross confirmation. Nevertheless, redundant sensors are also unreliable due to the same failure in many cases, so alternative approaches that rely on more fact-based means should be implemented.

4.1.2 Risks of Cyber Attacks

Being more and more digitalized and automated, current civil aviation autonomy systems are also being more and more attractive to cyberterrorists. The risk of cyber-attack and security breach is extremely dangerous. Cyber-attacks have the ability to paralyze flight control systems in flight, posing extremely worries about the potential devastating consequences [8]. In the communications sector, the Very High Frequency (VHF), the primary voice communication channel used by the industry, is susceptible to eavesdropping and jamming

due to a lack of encryption. An attacker can listen to ATC communications or block them entirely [8].
For navigation technologies, the Instrument Landing System (ILS), the most widely used autonomous landing systems in civil aviation, is critical for landing in low visibility. ILS has been demonstrated to be vulnerable to spoofing attacks. Researchers have shown the ability to manipulate cockpit indicators and even guide an aircraft towards an off-runway landing [8]. The ILS system is illustrated in figure 4, a failure in either the ILS system and the VHF radio will cause unimaginable effects.

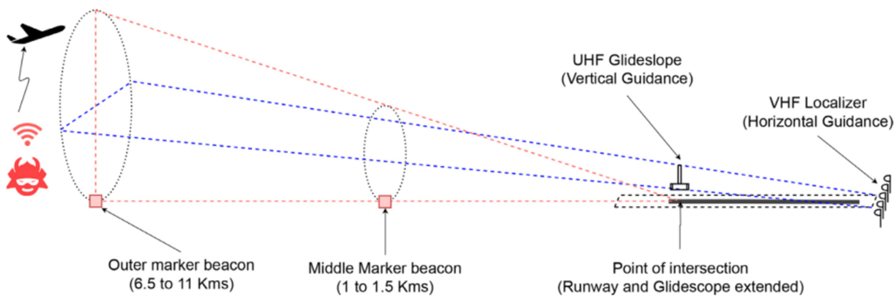

Fig. 4. Process of the Instrumental Landing System

In surveillance systems, the Automatic Dependent Surveillance–Broadcast (ADS-B) is a core technology for modern and future autonomous operations, as it pinpoints the location of aircrafts through a transponder onboard and broadcasts the plane's location in an open system. Its critical flaw is that it broadcasts unauthenticated and unencrypted data. This allows for eavesdropping: anyone can track any aircraft; message Injection: attackers can create fake aircraft on ATC screens; spoofing: attackers can alter the reported position of real aircraft.
Jamming: Attackers can block surveillance data [8].

4.1.3 Other technical challenges

For the ongoing development of autonomous systems, especially for the involvements of AI systems, brings the significant human factor challenges, primarily by reducing the pilot's situational awareness and creating an "out-of-the-loop" performance problem. Most importantly, ensuring robust autonomous decision-making under uncertainty remains a key technical challenge, particularly with AI methods that are difficult to fully verify and certify [10].

4.2 Current regulatory challenges and solutions

4.2.1 Pace of regulation renewal

As the technology of aviation autonomy thrived, the emerging problem is that the regulations of major authorities are not kept up with the fast technological advancements. This will likely result in the unfortunate situation of new technology being unable to be implemented in the real world [11]. Researchers have pointed out that the regulatory authorities, though seeking to tackle the problem, lack proper fundamental legal documents and guidelines to address the problem [8]. The human world manages its relationship with the rapidly evolving technology through regulatory authorities like the FAA [12]. The current FAA regulation regarding aviation autonomy is Title 14 Part 25 [3]. To ensure the continuous development of aviation autonomy, the regulation should be reviewed and ratified when necessary, and in addition, the introduction of a new fundamental guidance document should take place.

4.2.2 Lack of trust

Continue from the previous paragraph, there is a reason why major regulatory authorities are reluctant to keep up with regulation renewal regarding aviation autonomy. Authorities and the general public expect 100% assurance that these systems can be trusted, especially in emergency and critical decisions. A single mistake could lead to catastrophic disasters [13]. The Boeing 737 Max disaster in Indonesia and Ethiopia, which occurred in 2018 and 2019, respectively, is a real-world example. Due to a design fault in the MCAS (Maneuvering Characteristics Augmentation System) system, the two flights crashed nose down into the ground [12]. Therefore, the regulatory authorities have their proper reasons to be conservative in renewing regulations about aircraft autonomy. Nevertheless, it is believed that with more reliability tests and developments and proper guidance documents, flight automation systems will take a lead forward and benefit the aviation industry.

5 Conclusion

The development of aviation autonomy has made great progress in recent years. With the introduction of the CAPS systems and the implementation of the AutoSOAR system, the TASAR project, the levels of automation in civil aviation are able to march toward full autonomy in the near future. However, with technical limitations like sensor unreliability, system complexity, and the need for partitioned and modular avionics, and regulatory challenges like outdated regulations and distrust among authorities and the public in the new automation systems, the real-world implementation of these systems is highly restricted.

To address the challenges, more mature automation systems and more robust safety and reliability tests must take place, along with the introduction of guidance documents from authorities, in order to avoid the disasters of the AF447 flight and Boeing 737MAX. With the assistance of the newly developed Artificial Intelligence algorithms, it is believed that the aviation industry will eventually reach full autonomy in aircraft operation in the near future.

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