Evolution of Air Traffic Management Concept of Operations and Its Impact on the System Architecture

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(Received 18 June 2016; revised 20 July 2016; accepted 5 August 2016)

Abstract: The air traffic management system (ATM) has the task of ensuring safe, orderly and expeditious flow of air traffic. The ATM system architecture is very much dependent on the concept of operations (ConOps). Over the years the evolution in ConOps has resulted in changes in the ATM′s physical architecture, improving its physical infrastructure, increasing the levels of automation and making operational changes to improve air traffic flow, to cope with increasing demand for air travel. However, what is less clear is the impact of such changes in ConOps on the ATM′s functional architecture. This is vital for ensuring optimality in the implementation of the physical architecture components to support the ATM functions. This paper reviews the changes in the ConOps over the years, proposes a temporally invariant ATM functional model, and discusses some of the main key technologies expected to make significant improvements to the ATM system.

Key words: air traffic management; concept of operations; air traffic management(ATM) functions

CLC number: TN925 **Document code:** A **Article ID:** 1005-1120(2016)04-0403-11

0 Introduction

The air traffic management (ATM) system is a component of the air transport system (Fig. 1) that today includes aircraft, airline operations, airport operations together with the operational environment in which these components exist and interact.

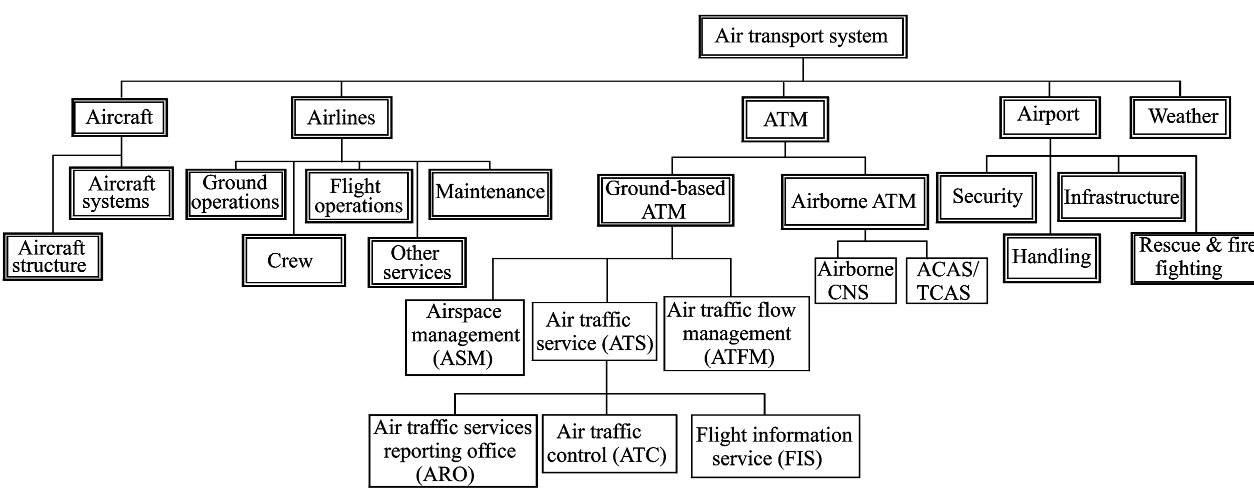

Fig. 1 The air transport system (ACAS-airborne collision avoidance system; TCAS-traffic collision avoidance system; CNS-communication, navigation and surveillance)

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How to cite this article: Washington Yotto Ochieng, Milena Studic, Arnab Majumdar. Evolution of air traffic management concept of operations and its impact on the system architecture[J]. Trans. Nanjing U. Aero. Astro., 2016,33(4):403-413.

http://dx. doi. org/10. 16356/j. 1005-1120. 2016. 04. 403

The international civil aviation organisation (ICAO) defines ATM as "an aggregation of the airborne functions and ground-based functions (air traffic services, airspace management and air traffic flow management) required to ensure the safe and efficient movement of aircraft during all phases of operations"[1]. The main objective of the ATM system is to enable aircraft operators to meet their planned times of departure and arrival, and adhere to their preferred flight profiles with minimum constraints and without compromising the required levels of safety[2]. As the demand for air travel has increased over the years, the ATM system has approached its capacity limits. In order to minimise delays and increase capacity, improvements in ATM have progressively been made in the form of changes to the concept of operations (ConOps) and the corresponding ATM system architecture.

The next Chapters use mainly Europe and the US (to a limited extent) as a case study to review the evolution of the ConOps and the impact on the functional and physical architecture of ATM. A time invariant functional model for ATM is derived and the key implementing technologies are discussed including benefits and challenges. This model should facilitate a holistic understanding of ATM including the interdependencies of the functional elements and their implementation. This understanding is critical to the realisation of an optimal ATM system that delivers the required performance in each of the main key performance areas (KPAs) of capacity, safety, environment and cost.

1 Evolution of ConOps

Aviation started in the period 1903 to 1911, with the Wright brothers' achievement of the first sustained, controlled, powered and heavier-than-air manned flight[3]. Thus the very first ConOps of ATM was that an aircraft carrying a human must rise by its own power into the air, and sustain itself without losing speed and land at a point, at least as high as, and at a given distance from, the starting point[3]. The aircraft was to be flown as far as possible for as long as possible and land undamaged. In this ConOps, the human had the sole responsibility for control including ensuring safe separation by visual means, from obstacles, the terrain and adverse meteorological conditions. As there was a single aircraft, the need for managing air "traffic" did not exist. A flag signal was used to "communicate" the right conditions for take-off. In addition to "communication", the only other functional requirement was to fly the aircraft. "Flight management" in this case was executed solely by the pilot. Technologically, the main enabler for this first motorised flight was the invention of the piston engine.

Later in this period, the ConOps evolved as a result of the the discovery of the commercial potential of flying. Aircraft were increasingly able to transport another passenger and/or goods in addition to the pilot. The importance of assuring safety of flight became apparent following the first fatal aircraft accident in 1908[4-5] caused by a failure of the propeller blade. In response, the pilot and passenger were required to wear safety belts and crash helmets[6]. Despite this tragic event, the number of aircraft and pilots rose gradually. This necessitated an operational change in the ConOps, in the form of the requirement for separation from other traffic to assure safety. The pilot was responsible for this employing visual means, i. e. "see and avoid" techniques. Fig. 2 presents the basic ATM functional architecture for this period, representing the bidirectional interaction between flight management and communication.

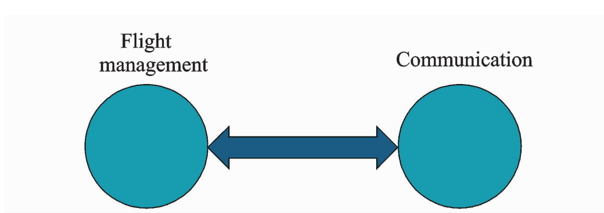

Fig. 2 Functional description of the ATM system in the period from 1903 to 1911

The next main period was during World War I when the ATM ConOps evolved to enable extensive use of aircraft, flown according to the mission assigned by the military. The pilot was responsible for the complete management of aircraft ensuring separation from surrounding traffic, obstacles, terrain and meteorological conditions through visual means i. e. "see and avoid". In addition to the flight management and basic communication functions, military missions (reconnaissance, artillery observation, bombing, and air combat) required the development of more sophisticated communication, navigation and surveillance (CNS) functions. Air-to-ground signalling techniques (including flags and flares, electric signal lamps, pyrotechnics and rockets) were used for communication. Furthermore, visual markers on the ground supported navigation and the pilot performed the surveillance function. Therefore, this period saw the addition of the navigation and surveillance functions to facilitate flight management (Fig. 3).

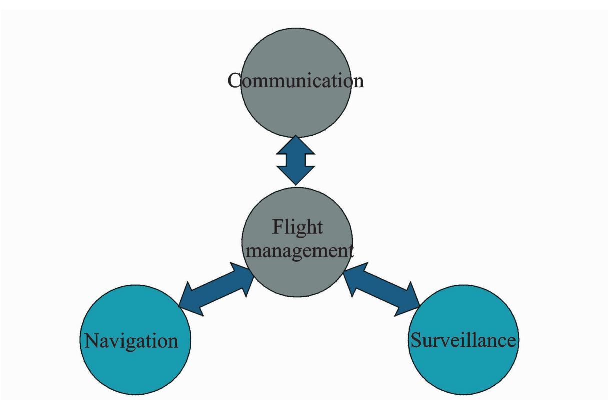

Fig. 3 Functional description of the ATM system during World War I

Unlike military aviation, the civil aviation sector stagnated during World War I. This was followed by the "Golden age of aviation" in the period between the two world wars, with major developments. This was due to the availability of many aircraft and pilots following the end of World War I, as well significant technological and regulatory developments. The evolution of the ConOps was driven by (1) aircraft transporting increased number of passengers, cargo and mail; (2) increasing range of air routes, ranging from short- to long-haul, and (3) flights in all meteorological conditions. The increased range and flight in all weather required changes to the existing CNS functions and the development of a new entity—air traffic services (ATS), including: Air traffic control (ATC), flight information service (FIS) and ATS reporting office (ARO)[1]. The ATC's role was to provide separation assurance between aircraft and obstructions, as well as to expedite and maintain an orderly flow of air traffic. The FIS was responsible for providing advice and information relevant to the safe and efficient conduct of flights. The ARO was tasked with collecting ATS reports, including flight plans submitted prior to departure.

The change of the ConOps following the introduction of ATS enabled pilots to fly in both visual meteorological condition (VMC) and instrumental meteorological conditions(IMC), during periods of reduced visibility. The navigation function evolved to enable pilots to rely on instruments on-board the aircraft, in addition to visual navigation. This was underpinned by the development of ground-based radio navigation aids: The automatic direction finder (ADF) and non-directional beacon (NDB). These developments spurred a rise in flights over Europe with the creation of the first commercial airlines, bringing with it the risk of collision. In response, a safety assurance function of the newly created ATC was introduced to assure aircraft separation.

The introduction of ATC resulted in the management of commercial aircraft by three stakeholders: Pilots, air traffic control operators (ATCOs) and airline dispatchers. At the departure airport, the ATCO issued an aircraft with the permission to take off using a coloured flag or light gun. During the airborne phase of operation, a pilot communicated their position to the ATCO over predefined points, thereby transferring the role of surveillance under IMC from pilots to ATCOs. Based on these position reports, ATCOs gained situational awareness of all air traffic and estimated future aircraft positions along their routes. This enabled ATCOs to issue direction instructions to subsequent points on the route and simultaneously ensure safe separation between the surrounding traffic during periods of IMC. Instructions issued by the ATCO were sent to the airline dispatcher who then transmitted them to the aircraft. Consequently, to support the ATC function, the communication function had to evolve to enable point-to-point radio communication between the airline flight dispatcher, the pilot and the ATCO. The introduction of ATC also changed the flight management function with pilots flying aircraft according to the instructions issued by the ATCO and the instruments on-board the aircraft.

In summary, this period saw the addition of one new function, safety assurance. The existing CNS and flight management functions evolved in implementation. Fig. 4 captures the functional architecture of the ATM during this period. A further development of note, was that the technological and operational developments arising out of World War I and the consequent growth in demand for air travel created the need for regulations to govern all aspects of civil aviation. Hence, the International Air Navigation Convention (ANC) at the Paris Peace Conference of 1919 and the Pan-American Convention in Havana of 1928 formulated the first set of civil aviation rules[7].

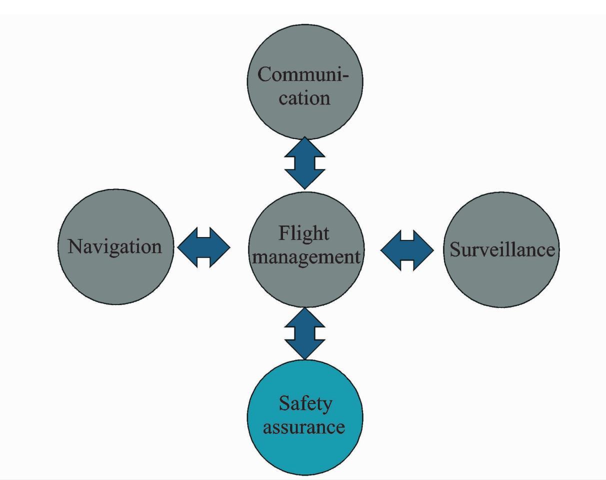

Fig. 4 Functional description of the ATM system between World Wars I and II

Due to the onset of World War II, the significant developments in ATM that occurred during the "golden age of aviation" were disrupted, particularly in terms of commercial air travel. Therefore, the ConOps was very similar to that during World War I, with the primacy of military requirements. Functionally there were no changes. However, there were improvements in the technologies implementing the functions. Communication was supported by radio, enabling direct communication between aircraft and the interception control centre. Navigation was based on visual references as well as ground-based navigation aids NDB and long range navigation (LORAN). Surveillance was provided by both ground-based radars (range and direction finding—RDF) and by airborne radars (air interception—AI). The combination of these two systems enabled flying at night and in IMC. However, the invention of the turbojet-powered aircraft during the latter stages of World War II was the major spur to the boom of civil aviation in the post-World War II period.

The growth in the number of aircraft together with their increasing speeds dictated the need for regulatory changes in the management of air traffic. Consequently at the end of the World War II, the need to establish globally harmonised rules, procedures and standards became apparent. In response, in December 1944, 52 countries created the Chicago Convention, which replaced the existing Paris and Havana Conventions. The Chicago Convention became the primary source of public international law, famous by its reciprocal commercial rights referred to as the "freedoms of the air"[8]. It also created the highest international aviation regulatory body, the International Civil Aviation Organisation (ICAO).

The next main period was between the end of World War II and 1960. Commercial aviation grew rapidly mainly due to the availability of mostly ex-military aircraft and their subsequent conversion into commercial aircraft. At the same time, new jet aircraft designs were introduced into service triggering a fundamental change in air transport. Aircraft were larger and could carry more passengers, had higher speeds and increased levels of comfort. An important lesson learnt during this period was from the large numbers of fight crews and aircraft lost during the World War II highlighting the fact that aircraft were becoming too complex to be managed by flight crews. This prompted the development of dedicated military safety centres[9-10] aimed at improving safety of aircraft and their systems in 1950s. This marked the start of research on human factors and ergonomics[11].

In the post-World War II period, the ATM ConOps mirrored that of the ″golden age of aviation″. Therefore, there were no additional functions, although technological developments during the war led to changes in the implementation of four existing functions: Communication, navigation, surveillance and safety assurance. Direct radio voice communication was established between the ATCO and the cockpit. Very high frequency (VHF) omnidirectional range (VOR) improved the navigation function by overcoming some of the limitations of NDB. Implementation of the primary surveillance radar (PSR) represented a major advancement in the surveillance function of commercial aviation enabling a reduction in procedural separation standards, thereby increasing airspace capacity. In addition, improved radar accuracy enabled a reduction in the number of position reports. ATCOs monitored the movement of aircraft on their radar screens. These changes in the CNS functions resulted in improvements in the safety assurance function of the ATM system.

The next major period in aviation was from 1960 to 1990, when the ConOps evolved triggered by the need to integrate air traffic services in Europe. This was initiated by the creation of the European Organisation for Safety of Air Navigation (EUROCONTROL), founded by six member states (Belgium, France, the Federal Republic of Germany, Luxembourg, the Netherlands and the United Kingdom). EUROCONTROL was aimed at improving the coordination of air traffic control by creating a collective air traffic control system[12]. Initially the main role of EUROCONTROL was to provide control to both civil and military traffic in the upper airspace, above 25 000 ft over the UK and 20 000 ft elsewhere. The division of airspace was based on the most-frequented routes and traffic zones, rather than national frontiers[13].

During the 1970s, as the cost of flying continued to decrease, the demand for civil air travel increased significantly resulting in congestion and significant delays. This necessitated improvement in the efficiency of the ATM system, via a change in the ConOps. It was no longer sufficient to fly aircraft for commercial purposes between origin and destination in all meteorological conditions. An increase in the efficiency in handling these flights was required in order to reduce the growing delays associated with the ATM system. A solution was the development of the flow and airspace management function and improvements in the navigation function to enable all aircraft operations (including landing) in all weather conditions.

Flow and airspace management was introduced in an attempt to protect national airspace initially from a surplus influx of aircraft. Five regional Flow Management Units in Europe (i. e. Frankfurt, London, Madrid, Paris and Rome) were established[12]. Initially, the lack of information exchange between the regional units (due to no direct data or voice links) resulted in regulation of flows at a local level, without consideration of the effect of this on the pan-European air traffic network.

The navigation function evolved with the introduction of the instrument landing system (ILS), which enabled approaches and landings in all meteorological conditions. In addition to the ILS, in the en-route phase, legacy navigation technologies were complemented with the distance measuring equipment (DME). In regard to surveillance, although PSR provided information about aircraft position, a key deficiency was the lack of information it provided about aircraft identity. This drawback was overcome with the implementation of the secondary surveillance radar (SSR).

Functionally, this period saw the most significant changes so far with the creation of three new functions (Fig. 5): Regional airspace management, regional flow management and regional information management. However, the uncoordinated regulation of flows and airspace configurations between states led to capacity imbalances between neighbouring states, and it became increasingly apparent that a European-wide solution for Flow and Airspace Management was needed.

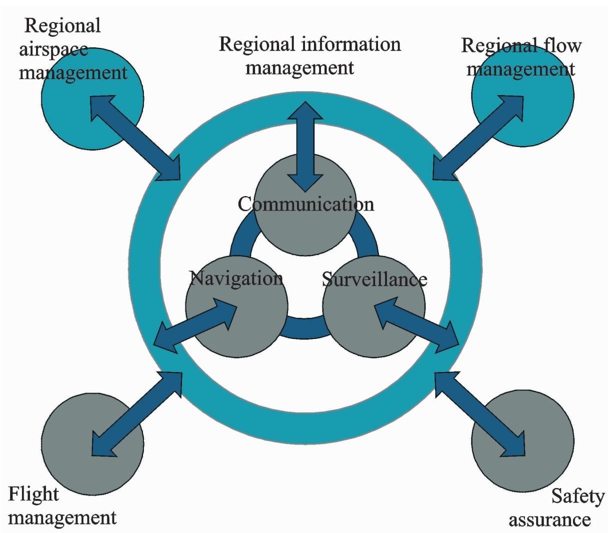

Fig. 5 Functional description of the ATM system between 1960 and 1990

Technological changes in the flow management, navigation and surveillance functions led to higher reliability and automation of the ATC function of separation management. The ATC function was divided between the civil and the military, with the former responsible for the provision of safe separation between aircraft and obstacles for commercial flights, and the latter for military flights. Therefore, the management of flights involved five stakeholders: Pilots, ATC, airlines, a regional flow management unit and the military.

All the safety efforts incorporated into the functional, technological and operational changes during this period resulted in a significant (1 500%) reduction in aircraft accident rates[14]. This improvement in safety can be partly attributed to the evolution in safety culture. While in the early days of the ConOps, the main contributing factor to accidents were mechanical failures, as shown in Fig. 6, the number of aircraft accidents gradually decreased in the period between 1970 and 1985. This decrease was mostly attributed to a reduction in mechanical defects on aircraft. In the 1980s and 1990s it became apparent that human factors and human errors played a significant role in system safety[15]. Consequently accident analysis and investigation expanded to include human aspects.

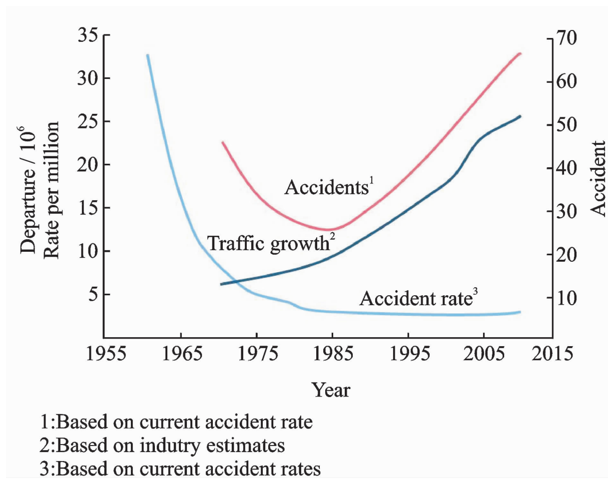

Fig. 6 Number of commercial jet accidents, accident rates, and traffic growth worldwide[5]

The next milestone period in aviation was between 1990 and 2005 during which high traffic growth, congestion and delays became critical. In addition to additional airport capacity, significant improvement in the efficiency of the ATM system was required, via changes to the ConOps. This was achieved through improvements in the ATM physical infrastructure and by increasing the levels of automation including transference of some responsibilities from human operators to machines.

Numerous initiatives were implemented (within EATCHIP, the European Air Traffic Control Harmonisation and Integration Programme) including building new en-route ATC centres, re-equipping existing centres, installation of new radar stations and improvement of the international ground-to-ground ATM communications infrastructure. The most significant change in the safety assurance function was the introduction of increased levels of automation through the airborne collision avoidance system (ACAS), for example the traffic alert and collision avoidance system (TCAS) on-board aircraft. The introduction of automation also resulted in a key change to the flight management function, in the distribution of the responsibility for aircraft separation assurance (in the en-route phase of flight) between the ATCO, pilot and automated systems. This improvement in the implementation of the safety assurance and flight management functions, while preventing many mid-air collisions, also created one of the most recent tragedies in aviation history: the überlingen mid-air collision[16]. This accident highlighted the importance of technical, organisational and political factors in assuring safety of the ATM system[17].

Increased automation was the main enabler for further improvements in the efficiency of the ATM system: It enabled the improved regulation of air traffic flow across Europe. This change in the ConOps was implemented through the creation of the central flow management unit (CFMU). Instead of regional flow management centres operated by national administrations, Air traffic flow management (ATFM) in the 36 European member states was increasingly coordinated and controlled by the CFMU at a pan-European level, leading to increased efficiency, additional capacity and reduced delays[18]. The regional flow management function was replaced by a centralised Network Management function that regulated any overloads that could arise when the demand exceeded capacity.

Lack of surveillance over oceanic and remote areas led to the requirement of procedural separation between aircraft, thereby restricting capacity in these areas. To solve this constraint, an initiative—future air navigation system(FANS) —was developed, contributing to a significant increase in capacity over oceanic areas. The key developments were improvements in: The communication function-transition from voice to digital communication; the navigation function—transition from inertial navigation system (INS) to satellite navigation (global navigation satellite systems, GNSS); and the surveillance function -transition from voice reports to automated digital reports via automatic dependent surveillance-contract (ADS-C) and automatic dependent surveillance-broadcast (ADS-B).

Additionally, advancements in navigation capabilities enabled the introduction of area navigation (RNAV) over a network of ground-based radio navigation aids (VOR, DME, VOR/DME, DME/DME and potentially based on GNSS). This led to improvements in route efficiency, reliability and safety. Furthermore, the ConOps also evolved for the airspace above territorial Europe where the efficiency of the ATM system was increased by reducing the required vertical separation minimum (RVSM) between aircraft[19]. In addition to RVSM, an increase in efficiency was achieved through closer coordination between civil and military air navigation, a result of the Flexible Use of Airspace (FUA) programme. The FUA resulted in improved airspace management, a significant reduction in airspace segregation needs, and consequently a net gain in capacity[18].

Finally all these operational changes in managing airspace led to a new centralised function - the Airspace Management (ASM) function-with the aim of adjusting the airspace to the predicted traffic demand. This function was further expanded with the development of the FUA concept, which adds a (near) real-time dynamic aspect to the ASM function thus enabling real-time airspace optimisation. When compared to the 1960—1990 period, this ConOps only evolved in the tendency to centralise already existing functions (i. e. centralised flow, airspace and information Management functions) as illustrated in Fig. 7.

From 2005 to date, despite the numerous changes made to the ConOps and ATM system since 1903 to account for the continuous growth in air traffic, delays and congestion persist. In response, the ICAO, EUROCONTROL and the European Commission (EC) have recommended further changes to the ATM system. The ICAO

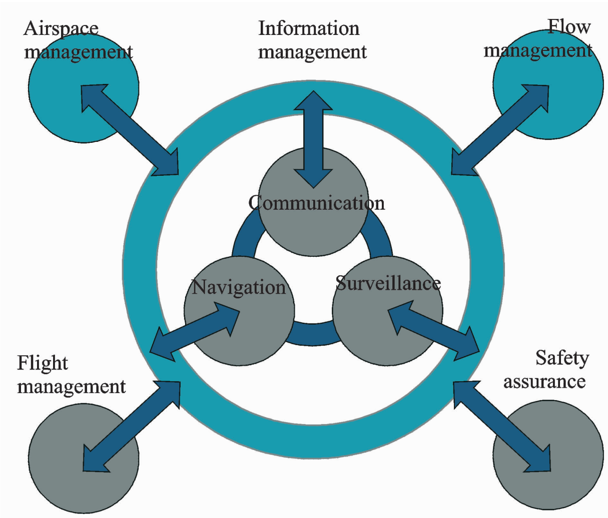

Fig. 7 Functional description of the ATM system between 1990 and 2005

developed the first Global Air Traffic Management Operational Concept, building on the FANS concept, to meet the needs of the ATM community to 2025 and beyond[20]. The main purpose of the new ICAO ConOps is to increase user flexibility and maximise the operating efficiencies, in order to increase system capacity, and improve safety levels for air traffic in the future. The ConOps not only focuses on an integrated and global ATM system but also introduces additional operational elements with respect to the FANS concept, such as performance-based and collaborative air traffic management[20].

Hitherto considered static without accounting for interaction between components, the new ConOps defines ATM as a dynamic, integrated management of air traffic and airspace (safely, economically and efficiently) through the provision of facilities and seamless services in collaboration with all stakeholders. Additionally the ATM system is defined as a system that provides ATM through the collaborative integration of humans, information, technology, facilities and services, supported by air and ground- and/or space-based communications, navigation and surveillance. These definitions also introduce new attributes of the future ATM system, highlighting dynamic and integrated management through the collaboration of all parties.

The ICAO ConOps introduces a paradigm shift from airspace-based to trajectory-based operations, implying that information on planned aircraft trajectories is used to adjust the airspace structures. This is in contrast to the previous airspace-based concept, in which airspace structures determined aircraft trajectories. The trajectory-based focus revolves around the concept of 4D trajectories that aims to improve predictability of air traffic by making the 4D aircraft state information available during any phase of the aircraft trajectory, both on the ground and in the air. By incorporating the spatial and time information, the scope of the flight management function needed to be expanded. This led to a creation of a new function, trajectory management. In addition, to cater for the changing societal needs, two new functions were created: security assurance and environmental management.

Based on the evolution of the ConOps to date and corresponding changes to the ATM system architecture, Fig. 8 presents a high level time invariant ATM functional architecture[21]. Table 1 summarises the purpose of each function. This functional architecture facilitates a holistic understanding of ATM including the interdependencies of the functional elements and their implementation. This is critical to the realisation of an optimal ATM system that delivers the required performance in each of the main key performance areas (KPAs) of capacity, safety, environment and cost.

2 Conclusions

This paper has reviewed the evolution of the ATM Concepts of Operations (ConOps) over the years starting from 1903 to date. The corresponding changes in the ATM's functional and physical architecture were identified, leading to a specification of a time invariant ATM system functional architecture. This is critical to the holistic understanding of the ATM system, its functional components and their interactions. Furthermore, it should facilitate the achievement of optimality in terms of the identification of priorities and the

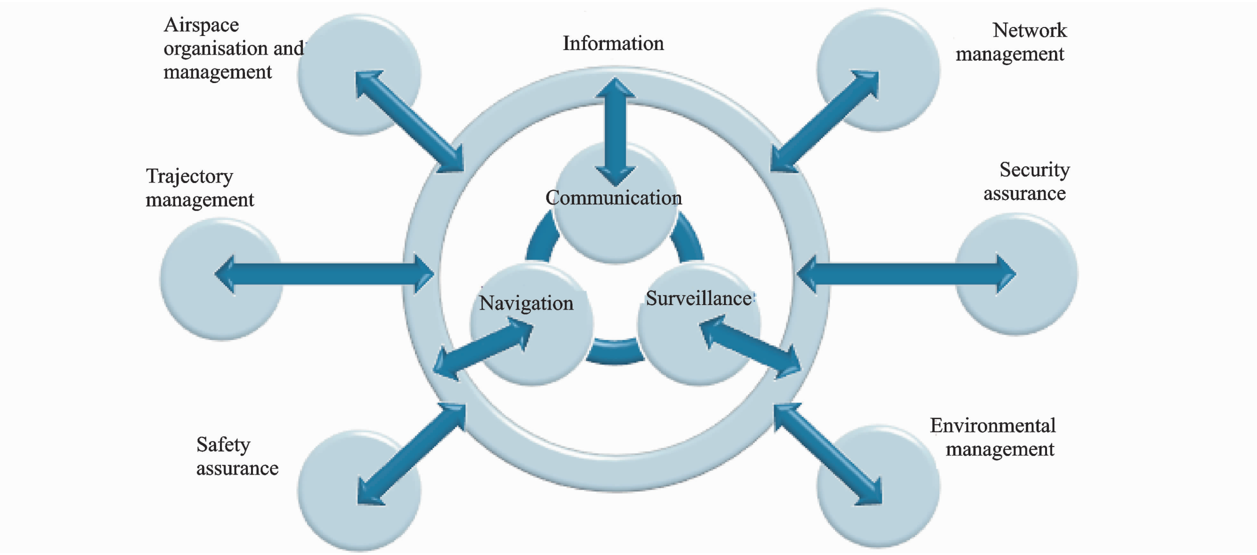

Fig. 8 Functional model for the ATM system ConOps between 2005 and 2025 (based on Ref. [18])

Table 1 Purpose of the ATM functions

Function name	Purpose
Communication	Enables point-to-point ground/ground (G/G), air/ground (A/G) and air/air (A/A) voice and data information exchange between stakeholders.
Navigation	Enables a stakeholder to locate the aircraft's present state or position and then to determine the course to steer to arrive at the next desired point both on the ground and in the air.
Surveillance	Broadcasts, receives, processes and displays information about the state or position, and/or identity, speed and future intent of aircraft, vehicles, obstacles and weather phenomena.
Information management	Receives, manages and distributes aggregated information from multiple services and stakeholders required for a timely, safe, efficient and cost-effective management of ATM operations.
Airspace organisation and management	Designs, allocates and coordinates civilian and military airspace at strategic, pre-tactical and tactical levels to achieve the most safe, efficient and harmonious use of airspace.
Network management	Ensure safe, orderly and expeditious flow of air traffic at strategic, pre-tactical and tactical levels by ensuring that air traffic control (ATC) capacity is utilised to the maximum extent possible, and that the traffic volume is compatible with the capacities declared by the appropriate air traffic services (ATS) authority. Encompasses the activities of air traffic flow management (ATFM).
Trajectory management	Ensures efficient management of four dimensional (4D) aircraft trajectories from en-route-to-en-route, whilst accounting for both airspace user preferences in terms of Key Performance Areas (KPAs) (i. e. capacity, safety, environmental impact, and cost) and the optimal network and airspace organisation and management solutions.
Safety assurance	Ensures conflict free management of 4D aircraft trajectories from en-route-to-en-route.
Security management	Protects the ATM system against airborne threats such as terrorist and illegal acts, attacks against infrastructure, cyber-attacks and electromagnetic attacks.
Environmental management	Reduces and manages the environmental footprint of aviation.

technologies required to implement the various functions to realise the targets set for the Key Performance Indicators (KPIs) for the KPAs of including capacity, safety, environment and cost.

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(Executive Editor: Zhang Bei)