Functional Allocation Approach for Separation Assurance for Remotely Piloted Aircraft

Gano B. Chatterji[*] and Vishwanath Bulusu[†]
Crown Consulting Inc. at NASA Ames Research Center, Moffett Field, CA, 94035-1000

Husni Idris[‡] and Jordan Sakakeeny[§]
NASA Ames Research Center, Moffett Field, CA, 94035-1000

A functional analysis framework is employed with the objective of exploring the separation assurance function for the remotely piloted aircraft system. The architecture of the remotely piloted aircraft system—highlighting several of the component systems and the functions resident onboard the remotely piloted aircraft and in the ground control station—is described to provide the context for understanding the complexity of the said system for a detailed functional analysis. The interactions between the agents of the separation assurance function belonging to the air traffic service provider, remotely piloted aircraft system operator and remotely piloted aircraft are described. Separation assurance by air traffic control, remain well clear by the remotely piloted aircraft system and collision avoidance onboard the remotely piloted aircraft are briefly discussed. The functional analysis framework is illustrated by relating the agents to the actions of (a) acquiring the surveillance information, (b) checking for conflicts, (c) creating the solutions for resolving conflicts and (d) implementing the conflict resolution solutions. This example is offered as a template by which a more detailed functional analysis of this and other functions could be developed. The architecture of the remotely piloted aircraft system is described to aid this process.

I. Introduction

Functional analysis of the separation assurance function for Remotely Piloted Aircraft Systems (RPAS) is conducted using the autonomy framework described in the accompanying paper—Ref. [1]. This autonomy framework consists of: (1) a formal process for functional allocation, (2) identification of agents (both human and machine) and their roles and responsibilities, and (3) determination of levels of autonomy (spanning the range from fully human to fully autonomous, and from centralized to distributed) needed for interactions between the agents for accomplishing the objectives of the function. The formal process for functional allocation used in this paper is a variation of the Observe–Orient–Decide–Act (OODA) process [2] called IISA process; it identifies functions for (1) Information Acquisition, (2) Impact Assessment (requiring mitigation), (3) Solution Planning and (4) Action Implementation (mitigation action). The objective of functional analysis is to determine system requirements—what it must do and how well it must be done—for accomplishing the mission objectives.

While separation assurance methods have been extensively studied over decades—see Ref. [3] for a survey—the objective of this paper is to use the separation assurance application to examine the unique aspects of the RPAS architecture that necessitates the use of automation and autonomy for enabling the integration of remotely piloted and autonomous aircraft operations in the US National Airspace System (NAS). Many of the challenges for these operations are because the information (voice and data) acquired onboard the aircraft need to be transmitted to the Ground Control Station (GCS) using radio links, and control instructions from remote pilot need to be uplinked to the aircraft using radio links, which depending on aircraft's location with respect to the transmitter is either direct Radio Line-of-Sight (RLOS) or indirect Beyond RLOS (BRLOS) using satellite. Error and failure characteristics of these links impact system design. When communication between the remote pilot and aircraft fails, the automation onboard the aircraft needs to continue flying the aircraft, land the aircraft or terminate the flight without affecting the safety of people, other aircraft, and infrastructure. Automation will also be required to enable capabilities that are equivalent to the capabilities of a manned aircraft by compensating for the inability of the remote pilot to see with the naked eye, feel the vibration and motion, hear the noise, and control the aircraft without communication latency. Several automation technologies developed for RPAS and its interaction with Air Traffic management (ATM) also have the

---

[*] Senior Scientist and Lead, Crown Consulting, Inc., NASA Ames Research Center, Associate Fellow.

[†] Aerospace Research Scientist, Crown Consulting, Inc., NASA Ames Research Center.

[‡] Aerospace Research Engineer, NASA Ames Research Center, Associate Fellow.

[§] Aerospace Engineer, NASA Ames Research Center, Member.

potential of advancing Urban Air Mobility (UAM)/Advanced Air Mobility, Unmanned Aircraft System Traffic Management (UTM), Upper Class E Traffic Management (ETM) and air traffic operations with manned aircraft. Functional analysis will illuminate requirements that may address these challenges.

The paper is organized as follows. Section II describes the RPAS and its architecture that includes the subsystems of the Remotely Piloted Aircraft (RPA), GCS and the communications system. While the architecture initially emerges from functional analysis, it also affects the functional analysis and requirements as it evolves. Architecture is discussed in this section to expose the reader to some of the complexities of such a system, and to provide the context for discussion of the agents and their interaction in Section III and functional analysis in Section V. Section IV discusses the separation assurance function. Subsequently, a functional analysis example featuring the separation assurance function is provided in Section V. The paper is summarized in Section VI.

II. Remotely Piloted Aircraft System Architecture

International Civil Aviation Organization (ICAO) defines the RPAS to consist of RPA, Remote Pilot Station (RPS), Command-and-Control (C2) link and other supporting components such as launch and recovery equipment [4]. They use the term RPS instead of GCS because the pilot station does not necessarily have to be located on the ground, as the word “Ground” in the Ground Control Station might suggest. They state that, while an RPA can be piloted from one of many RPS during a flight, only one RPS can be in control of the RPA at a given instant of time. The RPS can range from being a hand-held device to a multi-console station; it can be located inside or outside; and it can be stationary or mobile (onboard a vehicle, ship, or aircraft). The RPS is connected to the RPA via the C2 link for communication and data exchange. The link could be simplex or duplex, and direct RLOS or BRLOS. RLOS requires transmitter(s) and receiver(s) to be within each other’s radio link coverage range. Remote RLOS communications to the RPA can be achieved through a ground network, provided the transmitter is in RLOS to the RPA receiver. BRLOS is a configuration in which the transmitters and receivers are not in RLOS. BRLOS communications are usually accomplished via satellite systems and terrestrial networks which have longer transmission times than RLOS systems. The distinction between RLOS and BRLOS is whether a part of the communications link introduces appreciable or variable communications delay, not the architecture of the link.

References [4-6] describe several communication link architectures. Figure 1 shows the architecture in which the Air Traffic Control (ATC) voice and data are exchanged with the GCS using the RPA as a relay. This configuration requires a Very High Frequency (VHF) radio (two preferred for redundancy) onboard the RPA and a C2 link with adequate bandwidth for ATC voice and data exchange.

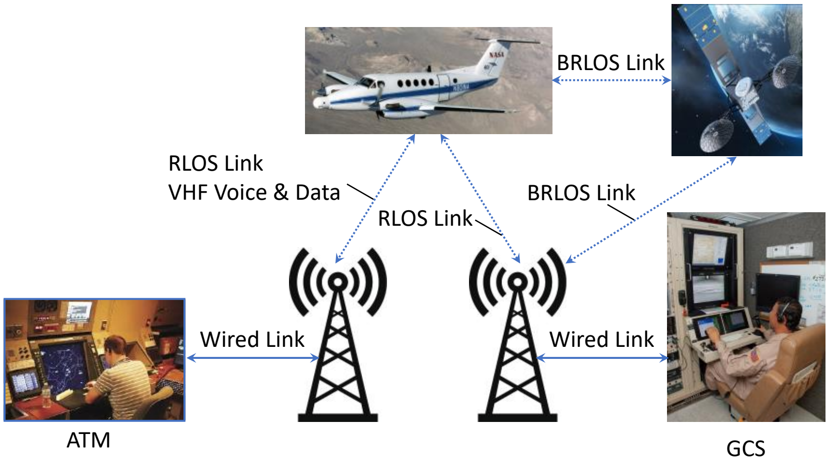

Figure 1. RLOS and BRLOS communication with voice and data relay via the RPA.

Figure 1 also shows a satellite link between the RPA and the GCS. In both the architectures—RLOS and BRLOS—shown in Fig. 1, the analog VHF voice messages received from the ATC are converted to digital onboard the RPA prior to relay to the GCS. These digital messages received by the GCS are converted to analog in the GCS for the remote pilot. Voice messages from the remote pilot are converted to digital in the GCS and transmitted to the RPA via the C2 link. The received digital messages are converted to analog onboard the RPA and relayed to the ATC via the onboard VHF radios. The RLOS and BRLOS links can also be used for Controller Pilot Data Link Communications (CPDLC).

Equipment requirements and operational responsibility for RPA operations are the same as for manned aircraft operations under Instrument Flight Rules (IFR) and Visual Flight Rules (VFR) [4]. However, it might be challenging for the remote pilot to recognize right-of-way situations and to take mitigating actions, especially in Visual Meteorological Conditions (VMC) (even while operating as an IFR flight) and in the presence of VFR traffic. To operate as a VFR flight, the remote pilot needs the additional ability to comply with the visibility and cloud clearance requirements. The remote pilot or RPA observer must maintain direct unaided visual contact with the RPA during Visual Line-of-Sight (VLOS) operations according to ICAO Annex 2 [4]. While the range and limits of safe VLOS operations are not defined, ICAO recommends due consideration be given to meteorological conditions, the size of the RPA for easy detectability by other aircraft and any other relevant factors. The horizontal range for VLOS operations is a function of the capabilities of the RPA observers in assisting the pilot in keeping the RPA separated from traffic and obstacles. It is also possible to increase the vertical range by suitably locating the RPA observer for example onboard a chase aircraft.

The ability to conduct Beyond Visual Line-of-Sight (BVLOS) operations, when neither the remote pilot nor RPA observers can maintain direct unaided visual contact with the RPA, requires additional equipment depending on the range and complexity. The ability to detect traffic conflicts and obstacles, and timely control actions for resolving conflicts and avoiding obstacles can be challenging in BVLOS operations especially due to C2 link failure and latency.

While ICAO allows for RPAS design with different systems and sensors for detecting and avoiding different hazards, they are expected to be interoperable for assuring coordinated mitigation of hazards especially when they occur at the same time. RPAS need to be suitably equipped with transponders and communication systems (voice and data) when operating in controlled airspace and under IFR with separation services provided by ATC. Detect-and-Avoid (DAA) equipment and procedures might also be needed for operating in controlled—and especially in uncontrolled—airspace for detecting hazards in addition to Mid Air Collisions (MAC).

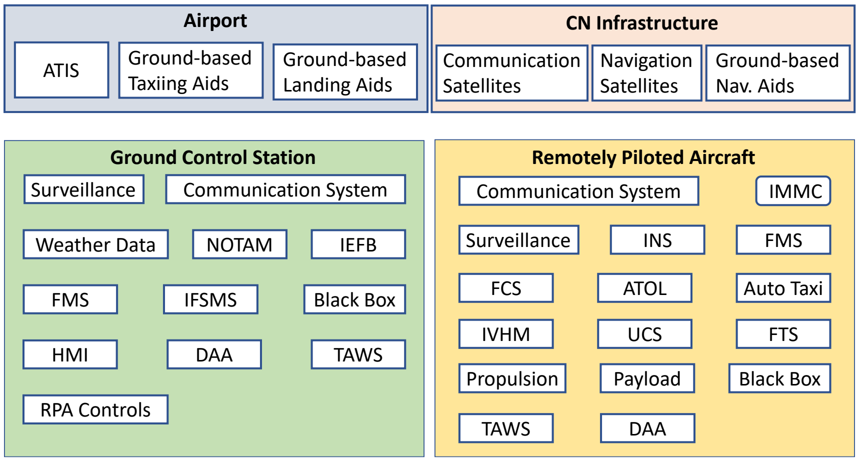

Figure 2. Remotely Piloted Aircraft System architecture.

The requirements outlined in the previous three paragraphs, and the known architecture of manned aircraft systems suggests the RPAS architecture shown in Fig. 2. Many of the elements of the architecture are derived from Fig. 2.3 in Ref. [7] and figures and descriptions in Chapter 1 of Ref. [8]. The Communication and Navigation (CN) infrastructure consists of communication satellites, navigation satellites and ground-based navigation aids. Communication satellites are used for information and command downlink and uplink when means for RLOS communication between GCS and RPA are unavailable. Navigation satellites such as the Global Navigation Satellite System (GNSS) provide positioning information to the RPA. GNSS information can be augmented with Ground-Based Augmentation System (GBAS) and Space-Based Augmentation System (SBAS) for improved position accuracy. Ground-based navigation aids such as Very High Frequency Omnidirectional Range (VOR), Tactical Air Navigation System (TACAN) and Distance Measuring Equipment (DME) provide bearing and range information to aircraft to enable them to navigate towards and away from the locations of these radio navigation aids. They also provide backup for failure of alternative means of navigation and for correcting navigation errors.

The airport infrastructure provides approach and landing aids such as Instrument Landing System (ILS), GBAS, Visual Approach Slope Indicator (VASI) and Precision Approach Path Indicator (PAPI) lights, lighting system consisting of centerline, landing zone, edge, and Runway End Identifier Lights (REIL) lights, and surface markings. Taxi aids include centerline and edge lights, markings, and signage. Conditions such as wind, weather, icing, braking, windshear, and bird strike for example near and at the airport surface, and in the terminal areas are provided in the Automatic Terminal Information Service (ATIS) broadcasts. Pilots listen to these reports as a part of the preparation for takeoff and landing. Pilots also receive advisories from ATC about hazardous conditions in the proximity of the airport. In addition to the existing infrastructure and means of communicating with the RP, automation enabled with sensors and wireless communication could be added to the airport infrastructure for RPA to taxi, takeoff, and land autonomously.

The RPA communication system consists of the Ultra High Frequency (UHF) and VHF radios; Ku-band and C-band transceivers; antennas; Mode-A, Mode-C or Mode-S transponders; and analog signal and digital data processing systems. Onboard Mode-C or Mode-S transponder is required by the ground-based ATC Radar Beacon System (ATCRBS) for receiving the aircraft ID and altitude information from the aircraft. The Mode-S transponder supports the functions of Mode-C and additionally enables onboard Airborne Collision Avoidance System (ACAS)/Traffic alert and Collision Avoidance System (TCAS) and Automatic Dependent Surveillance Broadcast (ADS-B) to communicate with others onboard proximate aircraft.

The RPA surveillance system includes ACAS Xu/TCAS-II, Air-to-Air Radar (ATAR), Electro-Optical (EO) systems such as steerable visual cameras, nosewheel camera, Forward Looking Infrared Camera (FLIR) and Light Detection and Ranging (LIDAR), ADS-B In and ADS-B Out, and C2 link for Ground Based Surveillance System (GBSS) data. GBSS information is derived from ground-based systems including from ATCRBS, ADS-B out broadcasts, Airport Surface Detection Equipment-Model X (ASDE-X) and radars that detect uncooperative aircraft. This information can be broadcast using a system such as Traffic Information System-Broadcast (TIS-B) for ADS-B equipped RPA. Select information in the proximity of RPA can also be uplinked to RPA via the C2 communications link from the GCS.

The Inertial Navigation System (INS) onboard the RPA fuses the data from Inertial Measurement Unit (IMU), which contains accelerometers, gyros, and magnetometers, GNSS and Air Data System to estimate the position (latitude, longitude, and altitude), groundspeed, true airspeed, calibrated airspeed, heading and course, Rate of Climb/Descent (ROCD), attitude consisting of quaternions and Euler angles, and the rotational rates about the body and inertial frames of references.

The Flight Management System (FMS) is a specialized computer that automates many in-flight piloting tasks for flying the aircraft. The pilot interacts with the FMS to select the different modes for performing the computations needed for generating the guidance information for flying the aircraft along the desired vertical and lateral trajectory. The FMS contains a navigation database and aircraft performance database. The navigation database contains airspace adaptation data such as waypoints, fixes, airways, airports, Standard Terminal Approach Routes (STAR), Departure Procedures (DP), DME, VOR, and Non-Directional Beacons (NDB) needed for creating and processing flight plans. The aircraft performance database from the aircraft manufacturer provides the information for setting the parameters such as speed for flying the desired trajectory. The performance database is created using aircraft performance parameters such as stall speeds, placard speeds, speed modes, approach speeds, thrust, drag, and fuel flow coefficients. An FMS capability can also be implemented in the GCS with aircraft state data downlinked from the RPA.

The flight plan needed for flying the lateral trajectory is created by the dispatcher and entered in the FMS by the pilot. The pilot can alter the flight plan as needed. Performance information such as gross weight, fuel weight and location of center-of-gravity is also entered during preflight phase. Modern FMS determine the aircraft state with information from INS, GNSS, DME and VOR. Position information from DMEs is obtained using a scanning procedure in which distances from five DMEs are used. Bearings to two VORs are also used for computing approximate position of the aircraft. The FMS constantly crosschecks information from various sensors and provides Actual Navigation Performance (ANP), a circle marking the position uncertainty. The FMS, coupled with autopilot and autothrottle for Lateral Navigation (LNAV) and Vertical Navigation (VNAV), provides roll steering command to the autopilot using LNAV, and speed (throttle) and pitch or altitude targets using VNAV. FMS also provides advisory information to the pilot, which the pilot can use to command autopilot and autothrottle.

Autopilot and autothrottle are parts of the Flight Control System (FCS). Texts also refer to FCS as the lower-level mechanical, hydro-mechanical, and fly-by-wire systems that move the aerodynamic control surfaces and change engine thrust. Autopilot controls the attitude of the aircraft; it generates commands for the control surfaces to point the aircraft in the desired direction, climb and descend. The autothrottle generates commands to control the engine thrust in the different modes of flight and achieve the desired airspeed. The autopilot and autothrottle work together to fly the aircraft along the vertical and horizontal trajectories. The Automatic Takeoff and Landing (ATOL) system of commercial aircraft uses information from FMS, ILS, and radar altimeter to generate instructions for autopilot and authrottle to control the landing of the aircraft. It also works with the autobrake system, thrust reversers and spoilers to slowdown and stop the aircraft. ATOL is especially useful in low visibility conditions. There are headwind, tailwind, and crosswind limitations for use of ATOL. Once the autoland is engaged, it can only be disengaged by disconnecting the autopilot or by initiating an automatic go-around.

The takeoff functions of ATOL in Ref. [7] are assigned to the Integrated Mission Management Computer (IMMC) in the military unmanned aerial platforms. For takeoff, ATOL will lock the spoilers down, release the brakes and set engine power for takeoff. It will generate commands for steering the nose wheel to compensate for crosswind for maintaining the aircraft on the centerline during the ground roll. It will issue commands to advance the thrust (Power Lever Angle (PLA) for turbine engine) in stages as the aircraft gains speed and the aerodynamic surfaces become active. It would then enable directional control working with the autopilot. A critical function of ATOL is takeoff abort management. Based on acceleration and critical speed thresholds, ATOL will either continue takeoff or reduce power and adjust the aerodynamic control surfaces to ensure weight on the wheels and stop the aircraft by applying brakes. Commands from GCS and ATOL can abort takeoff. ATOL can command abort based on speed-distance check, bank angle, roll rate, pitch angle, pitch rate, crosstrack deviation from centerline, crosstrack deviation rate, link failure and engine failure.

The Auto Taxi system will ingest information from onboard surveillance sensors and FMS, taxi instructions from the RP and the airport surface management system via the communications system, and the airport and obstacle geometry information from Navigation and Airport Mapping Databases to taxi safely along the route specified in the taxi clearance to the runway. It will hold short of the runways and stop at taxiway intersections as instructed by the airport surface management system via the communication system.

The responsibility of the Integrated Vehicle Health Management (IVHM) system is collecting data from the different onboard sensors and systems to improve operations and maintenance. IVHM detects and diagnoses onset of defects, analyzes the impact, and initiates maintenance workflows. IVHM data for abnormal functioning are provided to the GCS and to the workstations of the maintenance personnel.

The Utility Control System (UCS), defined in Ref. [7], will control and monitor fuel, hydraulic, electric and engine systems. The autobrake will send commands to the UCS for applying the brakes.

The Flight Termination System (FTS) [7] implements the intentional process to end the flight in a controlled manner in case of an emergency. The objective of the FTS is minimizing the possibility of injury or damage to persons, property, or other aircraft on the ground and in the air. The FTS might consist of a parachute release system, fuel release system, sensors for getting the data for decision making, and flotation devices for water landing, for example.

The aircraft propulsion system consists of the powerplant and the electronic and mechanical components of its control system. Modern commercial and military aircraft use a Full Authority Digital Engine Control (FADEC) system that employs a computer to control all aspects of the engine performance.

The payload system of a cargo aircraft consists of nets, attachment points on the floor and lateral tracks for containers. Cargo handlers have access to the cargo compartment via the cargo doors. Placement and weight of the payload affects the location of the center-of-gravity of the aircraft; therefore, weight and balance computation are required for proper load distribution.

The onboard Digital Flight Recorder ("Black Box") records voice and data in a continuous loop to support accident investigation. In addition to the one onboard the RPA, a Black Box in the GCS could record both information downlinked from the RPA and information such as ground-based surveillance data, weather data, message exchange between the RPA and RP, workflow logs, performance data from IVHM, ATC-RP voice data and RP-Crew voice data for example. These data could be kept for a longer duration because of computational and storage resources available on the ground.

The Terrain Awareness and Warning System (TAWS) checks for proximity of the RPA to the terrain both below and ahead of the aircraft. TAWS employs both a database of the terrain map and a radio altimeter; Class-A TAWS requires both; Class-B does not require a radio altimeter. It uses position and attitude information from the FMS for computations. It also provides a Premature Descent Alert when below the normal approach path to the nearest runway.

The purpose of the DAA system is to keep the own-aircraft away from other aircraft by the required minimum separation—DAA Well Clear (DWC)—by providing advisories to the RP. DAA uses information from the different surveillance sources to determine the trajectory of nearby aircraft, detects conflicts using the predicted trajectories, and generates maneuver guidance for the pilot. Reference [8] provides details of these functions. DAA also integrates Aircraft Collision Avoidance System (ACAS Xu) or Traffic alert and Collision Avoidance System (TCAS-II) for collision avoidance in addition to Remain Well Clear (RWC) for separation. ACAS Xu and TCAS-II use transponders to communicate with the aircraft in conflict to negotiate resolution maneuvers. Only vertical maneuvers are generated by TCAS-II. ACAS Xu generates both vertical and horizontal maneuvers.

In addition to the systems described above, modern transport aircraft are equipped with icing detection sensors, doppler radar for detecting convective weather and windshear, Fuel Quantity Indication System (FQIS), and Onboard Aircraft Weighing System (OBAWS). OBAWS provides information of the aircraft weight and location of the center-of-gravity when the aircraft in on the ground. It also provides the attitude of the aircraft on the ground. Data from OBAWS or Weight-on-Wheels (WoW) sensors inform the ATOL system whether the aircraft is airborne or on the ground, and whether the main wheels have touched down and the nose wheel is up or they have all touched down.

The IMMC is the electronic supervisor ("robot pilot") responsible for coordinating the actions of the different onboard systems to ensure that the RP's commands are faithfully followed, and contingencies are executed as planned. IMMC will implement the Automation and Emergency Recovery (A&ER) capability described in Ref. [7] and the Backup Control System mentioned in Ref. [9]. Appendix B of Ref. [7] lists requirements and assumptions of the A&ER capability. These include managing aircraft systems in normal conditions, performing checklists, automatically executing time-critical actions, automatically executing pre-planned actions during lost link, selecting pre-planned routes based on situation, reporting status and intent, managing failures, and prioritizing conflicting requests. IMMC would also automatically set the transponder to squawk codes to indicate lost link and lost DAA as a part of the actions discussed in Ref. [10].

The GCS gets surveillance information from GBSS and System-Wide Information Management (SWIM) feed. The sources of weather and wind data available to the GCS include Rapid Refresh (RR), High Resolution Rapid Refresh (HRRR), Traffic Flow Management (TFM) Convective Forecast (TCF), Corridor Integrated Weather System (CIWS),

Meteorological Aerodrome Report (METAR), Significant Meteorological Information (SIGMET), Airmen's Meteorological Information (AIRMET), and Pilot Reports (PIREP). The airspace restrictions—both permanent and temporary—hazards and abnormal conditions are available to the pilot in the Notice to Airmen (NOTAM).

The Integrated Electronic Flight Bag (IEFB), ingesting data from FMS, provides the RP the ability to perform flight planning calculations, see the location of the aircraft on the digital map of the airport surface, and display digital documentation for navigational charts, operations manuals, and aircraft checklists.

The Integrated Fault and Security Management System (IFSMS) will continuously ingest all the available planning and operational data available to the GCS and RPA to determine system failure, confidentiality, integrity and availability, trigger alarms, provide decision support, and implement mitigations. It will implement the cybersecurity framework of identify, protect, detect, respond, and recover.

TAWS can be implemented in the GCS with state information downlinked from the RPA. Class B TAWS—which doesn't need information from the radar altimeter—can be made to function with data derived from the GBSS. The airborne TAWS solution can be compared with the GCS-based TAWS solution for an integrity check. The separation assurance part of the DAA can be implemented in the GCS. Like in TAWS, surveillance information derived from GBSS can be used in the DAA for detecting conflicts and creating resolution advisories. The solutions can be automatically generated and displayed on the Cockpit Display of Traffic Information (CDTI). This trial-planning capability could be used by the RP to "self-separate" under VFR, and request clearance from ATC for flying an operationally beneficial route such as a direct route without causing separation issues under IFR.

The Human Machine Interface (HMI) enables the RP to visualize pertinent information and to set parameters for controlling the flight. The Electronic Flight Instrument System (EFIS) used in modern aircraft consists of a Primary Flight Display (PFD), Multi-Function Display (MFD) and Engine Indicating and Crew Alerting System (EICAS) display. The Primary Flight Display (PFD) shows the aircraft's speed, altitude, attitude, heading, speed target, altitude target and heading target. The MFD can be configured to display horizontal and vertical navigation data such as route and waypoints, moving maps, weather radar data, TAWS data, ACAS/TCAS data, and airport information. EFIS is assumed to be a part of the HMI in this paper. The HMI in GCS could also display camera images and computer-generated augmented reality images for providing situational awareness to the RP.

The RPA control system in the GCS should enable direct pilot control with stick, throttle, and pedals or with keyboard and mouse; control via autopilot entry; and by waypoint entry in the FMS. Furthermore, it should enable the RP to directly command lowering and raising of landing gear [9], dumping of fuel, activating the FTS, and selecting flight and communication modes. The RP should also be able to override non time-critical actions of the onboard IMMC.

III. Agents and Interaction

The IISA process employed in this paper requires identification of the agents and their roles and responsibilities. Three agents that emerge from the discussion in the previous section are the RP, ground crew, and the IMMC representing the RPA. Dispatcher is another agent employed by the aircraft operators. The Aircraft Dispatcher is a licensed airman jointly responsible with the pilot for operational control and safety of flight. The dispatcher ensures the planned operations are compliant with the government and company regulations including those for the crew and equipment for legally operating the flight. The dispatcher creates a flight by associating the pilots and the crew to the physical aircraft for transporting passengers and cargo from the airport of origin to the airport of destination. After arrival at the airport of destination, the crew, passengers and cargo, and the physical aircraft are assigned to a different flight. The dispatcher is responsible for ensuring the crew can get to the aircraft, aircraft are available, and the passengers can get to their destination. To recover the schedule from abnormal operations caused by flight cancellations due to severe weather, for example, crew from different locations and at times empty aircraft need to be repositioned to operate the flights. An important service provided by the dispatcher is preparation of the flight plan considering airport conditions, weather and wind reports, Severe Weather Avoidance Plan (SWAP), TFM initiatives, PIREPs, NOTAMs, Minimum Equipment List (MEL), and maximum permitted takeoff and landing weights. The dispatch function includes weight and balance calculations, aircraft loading schedule and constraints, and takeoff power settings. The dispatcher also determines the amount of fuel required for operating the flight in consultation with the pilot-in-command based on the aircraft performance characteristics for flying the distance between the origin and destination, distance to the alternate airport, and additional fuel required by regulation and needed for avoiding regions affected by severe weather. The dispatcher also follows the flight on the workstation, displaying aircraft state information downlinked from the aircraft, and communicates with the pilot regarding conditions affecting the flight such as meteorological conditions (icing and turbulence) and conditions at the destination airport (braking conditions and arrival/departure directions). The voice and message communication between the dispatcher and pilot is accomplished with High Frequency (HF)/VHF radios and satellite communication. Airlines use the commercially available Aircraft Communications, Addressing and Reporting System (ACARS), which is a digital datalink system that uses HF/VHF radios and satellite communication. ACARS is also integrated with the FMS for dispatch to uplink flight plans directly to the FMS. The pilot can accept the loaded flight plan and make it active.

The two other agents from the ATM system that enable RPAS operations are the air traffic controllers and the TFM personnel. Air traffic controllers use cognitive analysis supported by tools that display track history and trend vectors—short duration forecasts—for determining conflicts between pairs of aircraft and developing strategies for resolving them. They issue clearances to the pilot such as climb/descend, reduce/increase speed, or change heading to resolve conflicts. Modern Decision Support Tools (DSTs) deployed in the Air Route Traffic Control Centers (ARTCC), Terminal Radar Approach Controls (TRACON) and Air Traffic Control Towers provide trajectory-based advisory information to assist controllers with conflict detection and resolution (see Refs. [11] and [12]), metering and sequencing tasks. Trajectories are predicted by employing aircraft performance and atmosphere models, wind data, flight plan and track data. The aircraft performance model specifies takeoff weight, thrust, drag, fuel burn, climb, cruise and descent calibrated airspeed/Mach, and speed and altitude thresholds for transitioning from one flight mode to the next such as from climb to cruise, cruise to descent and approach to landing. The flight plan defines the horizontal path from origin to destination, cruise altitude and cruise speed.

A conflict between a pair of aircraft is determined by checking the distance between their forecast trajectories at discrete intervals against the minimum separation standard. After conflict detection, a process called trial planning is initiated to resolve the conflict. Trial planning, as the name suggests, uses trajectory prediction repeatedly with different values of control variables such as speed, heading, altitude and combinations of them for creating alternative trajectories. These trajectories are then examined for conflicts. Control variables associated with conflict-free trajectories are then displayed on the DST as choices to the controller for providing advisories to the pilots.

The goal of national TFM is to prevent the traffic demand from exceeding the available capacity of NAS resources because it directly affects safety. TFM initiatives are often required during severe weather conditions because weather reduces both airspace and airport capacity. Predictions of weather and traffic demand in the airspace and at airports are employed by the Air Traffic Control System Command Center (ATCSCC) to form strategic plans from an hour to 24-hour time horizon. Some of the mechanisms employed for national TFM are Airspace Flow Programs (AFP), Ground Stops (GS), Ground Delay Programs (GDP), and National Playbook [13]. Regional traffic flow management, which operates on a 20-minutes to two-hour time horizon, adjusts flow control actions based on near-term forecast of air traffic demand, airspace capacity and weather while preserving the national flow management objectives set by the ATCSCC. These adjustments are made by Re-Routing (RR) flights, distancing flights spatially with Miles-In-Trail (MIT) and distancing them temporally with Minutes-In-Trail (MINIT). These restrictions are used both in the enroute and terminal airspaces. They are routinely used along center boundaries to control (meter) the inbound and outbound flow rates. Traffic Management Coordinators (TMC) communicate with air traffic controllers to have them issue clearances to pilots for achieving the flow management objectives. A more comprehensive discussion on separation assurance and TFM is provided in Ref. [14].

The interaction between the agents is summarized in Fig. 3. The Airline ATC Coordinator, a dispatcher, in the Operations Control Center attends the telephone conferences organized by the ATCSCC to discuss the TCF, flow constraints, SWAP and TFM initiatives. The ATC coordinator also communicates with the TMC about TFM constraints and issues affecting their flights. The dispatcher does not talk to the air traffic controller, and the pilot does not talk to the TMC. The dispatcher talks to the pilot, crew, and maintenance to address issues discovered during preflight checks, and adjusts the flight plan and the amount of fuel to be put in the aircraft. Dispatchers also interact with pilots during flight if there is an off-nominal event like a mechanical issue with the aircraft or a medical emergency on the flight. The IMMC in the RPA sends information to the RP and receives command-and-control instructions from the RP via the GCS. Only RPs are authorized to provide command-and-control instructions to the RPA. The onboard IMMC does not interact with the ATM system; it sets transponder codes to squawk lost link, lost DAA and other failure conditions for reception by the ATC automation.

IV. Separation Assurance

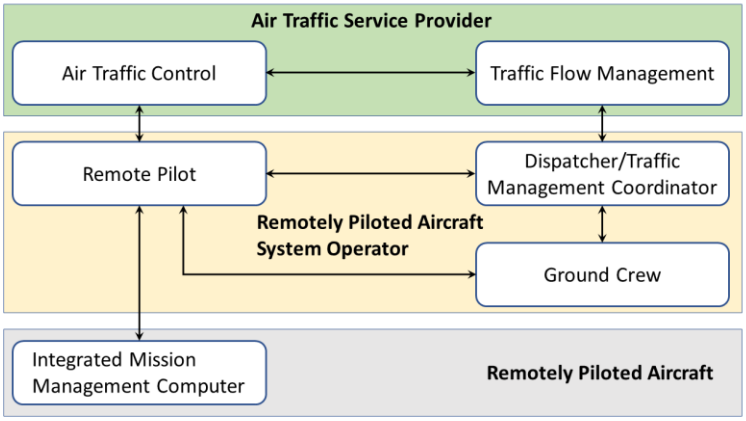

Figure 3. Agents and their interaction.

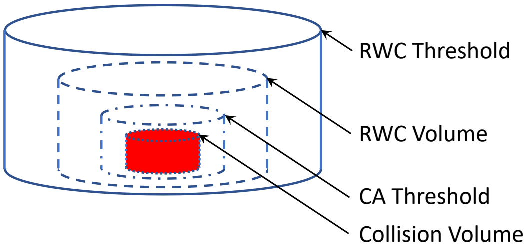

Figure 4. RWC and CA geometries from Ref. [16].

Reference [15] describes the DAA function in three categories: strategic conflict management, separation provision by ATC and/or RWC by RPAS, and collision avoidance. Strategic conflict management is achieved by airspace organization and management, demand-capacity balancing, and traffic synchronization. TFM procedures such as metering, scheduling, and sequencing are used for this purpose. The separation provision process for detecting conflicts and generating resolution advisories by the ATC was briefly described in the previous section. The same trajectory-based Conflict Detection and Resolution (CDR) process can be employed by the DAA system onboard the RPA by using the onboard surveillance data, discussed earlier in Section II, to track the nearby aircraft and predict their trajectories. This same CDR process can also be implemented in GCS using surveillance data from GBSS and downlinked from the RPA. The solutions generated by the ATC DST, RPA DAA and GCS DAA can be crosschecked for validity. Collision Avoidance (CA) is triggered when the separation provision process fails to resolve the conflict. The TCAS and ACAS have been used in commercial aviation since the 1980's. ACAS/TCAS utilize Mode-C and Mode-S transponder signals to alert the pilots of proximate aircraft about potential incursions and provide coordinated resolution advisories for preventing Midair Collision (MAC). Figure 4 shows the RWC and CA geometries defined by concentric cylindrical regions with the RPA in the center of the collision volume.

While the concept of CDR is straightforward, it becomes challenging because of conflicts between aircraft with vastly different performance characteristics and being in different phases of flight—one in climb and the other in cruise for example—and due to uncertainty in the future trajectory intent and parameter uncertainties.

Further research is needed for characterizing conflicts between RPA and another RPA due to the possibility of C2 link failures affecting both aircraft, commercial aviation aircraft, general aviation aircraft, airships, UAM aircraft and small drones. Several other types of aerospace vehicles such as supersonic/hypersonic aircraft, Space Launch Vehicles (SLV), High-Altitude Long Endurance (HALE) aircraft, and High-Altitude Balloon Systems (HABS) are expected in the future. These types of aircraft are expected to transition through the RPA cruise altitude as they climb to higher altitudes. ATC will ensure separation of RPA aircraft operating under IFR. ATC will also issue Temporary Flight Restrictions (TFR), which will cause the Dispatcher to issue/modify a flight plan compliant with the TFR, and the RP to keep the RPA away from the TFR region while it is active. For RPAS operation under VFR, information exchange and coordination with the UTM ([17]) and UAM ([18]) systems will be required, especially during RPA climb and descent through their operational altitudes.

To address the uncertainty in knowledge of pilot intent, intended route and the climb/descent parameters, Ref. [19] predicts multiple trajectories in the horizontal and vertical plane for separation assurance. The main issue with checking for conflicts with multiple trajectories is the increased likelihood of false alarms. Reference [19] discusses several mitigation methods for reducing false alarms. Figure 5 shows the scenario of aircraft deviating from the planned flight route. The logical guesses in this situation are: (1) the aircraft will continue flying at the same speed and heading—Dead-Reckoning (DR) trajectory—and (2) the aircraft is going to return to the original flight plan route—Flight Plan (FP) trajectory. The Tactical Separation-Assisted Flight Environment (TSAFE) procedure of Ref. [19], predicts both the DR trajectory and the FP trajectory of a pair of aircraft, and compares their combinations—DR1/DR2, FP1/FP2, DR1/FP2 and FP1/DR2—where the 1 and 2 are indices of the aircraft, for CDR. The gray region in Fig. 5 is the manifold of RWC regions, where the RWC is a circular region of radius "RWC Threshold" in the horizontal plane. Alternative trajectories are also predicted in the vertical plane as shown in Fig. 6. Figure 6 shows predicted vertical trajectories accounting for the expected future altitude amendment, or the altitude issued by ATC in the clearance. The DR trajectory assumes flight continuing at the current altitude. The other trajectories assume fast and slow rates of climb to the cleared or expected altitude. Observe the RWC vertical extent of "RWC Threshold" shown in Fig. 6. Also, note the hashed region, which is also included in the manifold because the actual climb trajectory can be anywhere between the fast and slow trajectories. Unlike combinations of horizontal trajectories, the manifold of RWC of vertical trajectories is considered. With M1 and M2 being the RWC manifolds of vertical trajectories of Aircraft 1 and 2, the combinations examined with the horizontal trajectories are DR1+M1/DR2+M2, FP1+M1/FP2+M2, DR1+M1/FP2+M2 and FP1+M1/DR2+M2.

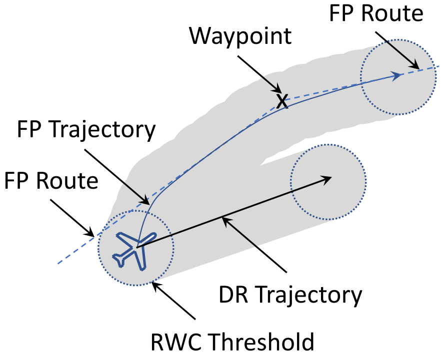

Figure 5. Flight plan-based (FP), and dead-reckoning (DR) predicted trajectories from Ref. [19].

The TCAS-II logic, described in Ref. [20], employs time-to-go to the Closest Point of Approach (CPA) instead of distance to determine issuance of a Traffic Advisory (TA) or a Resolution Advisory (RA). The time to CPA is termed "range tau" and the time to co-altitude is termed "vertical tau." Range tau is computed as the ratio of slant range to the closing speed between a pair of aircraft. The vertical tau is similarly determined as the ratio of the altitude separation to the vertical closing speed. A TA or a RA is displayed to the pilot only when both the range tau and vertical tau are less than the specified threshold values, which are a function of the altitude. Table 2 in Ref. [20] provides these thresholds with associated altitude range and sensitivity level.

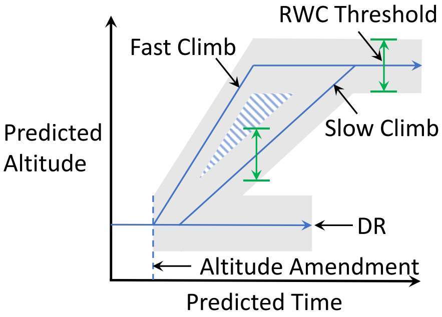

Figure 6. Fast and slow climb, and dead-reckoning predicted vertical trajectories from Ref. [19].

An issue with the definition of tau is that, when the rate of closure is very low, such as in shallow angle encounters, an intruder aircraft can come very close in range without the range tau falling below the TA or RA trigger thresholds. To guard against this type of encounter, a modified definition of range tau (simple range tau with an added compensation term) is employed such that TAs and RAs are triggered at or before the specified DMOD range threshold. To deal with low vertical closure rates, the vertical tau is also modified to trigger TA and RA at or before the specified ZTHR vertical threshold. In addition, a vertical threshold value ALIM is used to determine if a particular RA is corrective or preventive. The DMOD, ZTHR and ALIM values are also provided in Table 2 in Ref. [20].

V. Functional Analysis of Separation Assurance Function

Functional Analysis is part of the Systems Engineering Process (SEP), which seeks to codify a set of requirements into system and process descriptions and generate information and input for each level of development leading to implementation of the system [21]. This iterative solution process (see Figure 3-1 in Ref. [21]) is applied sequentially with information from analysis to guide next levels of development. Salient features of SEP include inputs and outputs, requirements analysis, functional analysis and allocation, requirements loop, synthesis, design loop, verification, and system analysis and control.

Functional analysis views the system from the top—highest level of abstraction—and logically layers the functions into subfunctions at increasing levels of detail. Several different functional analysis approaches are employed for exposing aspects of the system [22]. The Functional Identification Diagram approach, discussed in Ref. [22], has been employed in this paper. Figure 7 shows the diagram at the highest level. Note the IISA steps, described in Ref. [1], indicated by the blocks numbered 1 through 4. The tree resulting from the functional analysis is shown in Fig. 8. The terminal nodes of this tree are the agents described earlier in Section III. The acronyms in Fig. 8 that were not defined earlier are Aircraft Dispatcher (AD) and Provider of Service for RPAS (PSR). The actions associated with the reference numbers in Fig. 8 are listed in Table 1.

The information in Fig. 8 and Table 1 should be considered an example rather than complete functional analysis necessary for designing and implementing the integrated separation assurance considering the solutions provided by

ATC, created by the RP using information from DAA, TAWS and other GCS systems, and determined onboard the RPA with information from DAA, TAWS, FMS, and other systems. For complete analysis, one would need to consider all the systems that provide aircraft state and surveillance information, modes of flight, failure conditions, discrepancies in the data generated by different ground-based and airborne systems, time criticality, decision thresholds and information loops for example. The main takeaway from this example is that the IISA framework can be employed for detailed functional analysis with some understanding of components, processes and agents that could be integrated for composing the desired function.

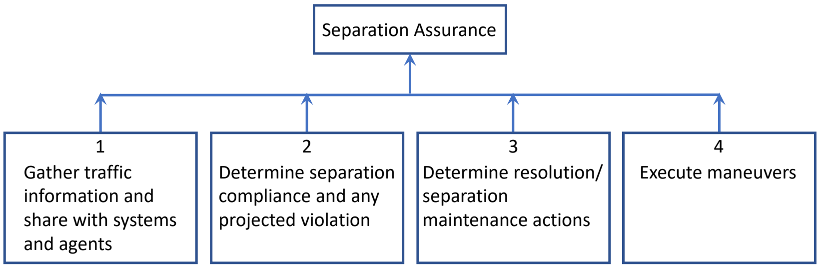

Figure 7. Functional identification diagram for separation assurance function at the highest level.

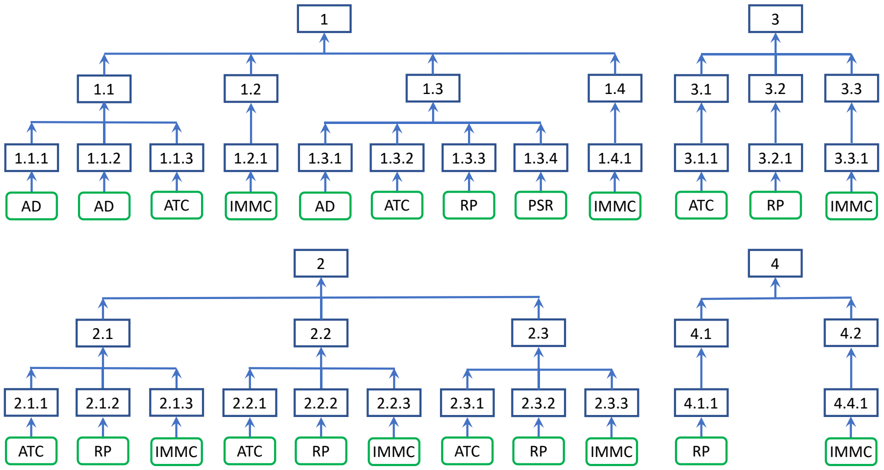

Figure 8. Hierarchical functional identification diagram for separation assurance function.

Table 1. Functional analysis of the separation assurance function.

Level 0	Level 1	Level 2	Level 3	Actions	Agent
Separation Assurance				Separation assurance	
	1			Gather traffic information, and share	
		1.1		Gather information from ground-based sources	
			1.1.1	Create flight plan following dispatch regulations	Dispatcher
			1.1.2	Obtain meteorological information	Dispatcher
			1.1.3	Obtain track information derived from surveillance	ATC
		1.2		Gather information from airborne sources	
			1.2.1	Obtain data/information from onboard sensors including: • Sensor performance, update rate; link performance; GNSS jamming; intruder state data/track information • Meteorological conditions, ambient temperature, visibility, icing, turbulence	IMMC
		1.3		Share information from ground-based sources	
			1.3.1	Share flight plan and meteorological information	Dispatcher
			1.3.2	Share surveillance information, TIS-B, SWIM	ATC
			1.3.3	Share plans, control, and contingency information	RP

			1.3.4	Share information provided by service providers	PSR
		1.4		Share information from onboard sources	
			1.4.1	Share information from onboard sensors	IMMC
	2			Determine separation compliance and any projected violation	
		2.1		Check current separation	
			2.1.1	Check states of nearby aircraft against separation minimums	ATC
			2.1.2	Check states of nearby aircraft on CDTI against separation minimums	RP
			2.1.3	Use onboard traffic information to check separation	IMMC
		2.2		Predict trajectories, and detect separation violations	
			2.2.1	Predict trajectories, and determine CPA and time-to-go to CPA	ATC
			2.2.2	Predict trajectories with GCS data; determine CPA and time-to-go to CPA	RP
			2.2.3	Predict trajectories with onboard data; determine CPA and time-to-go to CPA	IMMC
		2.3		Check if conflict/collision resolution needed	
			2.3.1	Check based on CPA and time-to-go using ground-based information	ATC
			2.3.2	Check based on CPA and time-to-go using GCS-based information	RP
			2.3.3	Check based on CPA and time-to-go using onboard information	IMMC
	3			Determine resolution/ separation maintenance actions	
		3.1		ATC generated solution using information from ground-based sources	
			3.1.1	Use DST to create trial plans and check if conflict will be resolved	ATC
		3.2		RP generated solution with GCS information from airborne & ground sources	
			3.2.1	Use GCS DAA to create trial plans and check if conflict will be resolved	RP
		3.3		RPA generated solution with information from airborne sources	
			3.3.1	Use onboard DAA to create trial plans and check if conflict will be resolved	IMMC
	4			Execute maneuvers	
		4.1		RPA executes RP commands	
			4.1.1	Send solution via C2 link	RP
		4.2		RPA executes IMMC commands	
			4.2.1	Implement onboard DAA solution	IMMC

VI. Summary

The separation assurance function of the remotely piloted aircraft system was analyzed using a functional analysis framework. Many of the systems that are expected to reside onboard the remotely piloted aircraft and in the ground control station, and their functions were described. Some understanding of the architectural components that can be assembled for implementing the desired function is helpful for functional analysis. The functional analysis in turn helps identify missing requirements for improving the design and eventual implementation of the desired function. The agents identified were: (1) the air traffic service provider agents—air traffic controller and traffic flow management; (2) remotely piloted aircraft system agents—remote pilot, aircraft dispatcher and ground crew; and (3) remotely piloted aircraft agent—Integrated Mission Management Computer. Their actions and interactions with each other were described. The sub tasks within the separation assurance function discussed were: (1) separation provision by air traffic control, (2) remain well clear by the system onboard the remotely piloted aircraft and in the ground control station, and (3) collision avoidance. Finally, a functional analysis example of the separation assurance function was presented to illustrate the framework relating the agents to the actions of information acquisition, impact assessment, solution planning and solution implementation. This example and the remotely piloted aircraft system architecture described in the paper can be followed for developing a more detailed functional analysis of the detect-and-avoid function and other functions of the remotely piloted aircraft system.

References

[1] Sakakeeny, J., Jack, D. P., and Idris, H., "A Framework for Dynamic Architecture and Functional Allocations for Increasing Airspace Autonomy," *AIAA Aviation Forum*, Chicago, IL and online, June 27-July 1, 2020.

[2] Richards, C., "Boyd's OODA Loop," *Necesse*, Vol 5, Issue 1, 2020, URL: https://fasttransients.files.wordpress.com/2020/03/boydsoodaloopnecesse-1.pdf

[3] Bilimoria, K. D., "Survey of Air/Ground and Human/Automation Functional Allocation for Separation Assurance," 12th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference and 14th AIAA/ISSM, September 17-19, 2012, Indianapolis, Indiana.

[4] International Civil Aviation Organization, "Manual on Remotely Piloted Aircraft Systems (RPAS)," Doc 10019, First Edition, 2015.

[5] Radio Technical Commission for Aeronautics (RTCA), "Command and Control (C2) Data Link Minimum Aviation System Performance Standards (MOPS) (Terrestrial)," RTCA DO-362, 1150 18th Street NW, Suite 910, Washington, DC 20036-4001, December 17, 2020.

[6] Radio Technical Commission for Aeronautics (RTCA), "Minimum Aviation System Performance Standards for C2 Link Systems Supporting Operations of Unmanned Aircraft Systems in U.S. Airspace," RTCA DO-377, 1150 18th Street NW, Suite 910, Washington, DC 20036-4001, March 21, 2019.

[7] European Organization for Civil Aviation Equipment (EUROCAE), "Minimum Aviation System Performance Standards (MASPS) RPAS Automation and Emergency Procedures (A&ER)," Draft ED-281, May 2020.

[8] Radio Technical Commission for Aeronautics (RTCA), "Minimum Operational Performance Standards (MOPS) for Detect and Avoid (DAA)," RTCA DO-365B, 1150 18th Street NW, Suite 910, Washington, DC 20036-4001, March 18, 2021.

[9] Merlin, P. W., "Crash Course—Lessons Learned from Accidents Involving Remotely Piloted and Autonomous Aircraft," NASA Aeronautics Book Series, National Aeronautics and Space Administration, 2013.

[10] Department of Defense, "Unmanned Aircraft Systems Airspace Integration Joint Test (UAS-AI JT): UAS National Airspace System Flight Operations Standardized Procedures (UNFO SP)," July 21, 2015.

[11] Erzberger, H., "Transforming the NAS: The Next Generation Air Traffic Control System," *Proceedings of the International Congress of the Aeronautical Sciences (ICAS)*, Yokohama, Japan, August 30, 2004.

[12] Erzberger, H., "Automated Conflict Resolution for Air Traffic Control," *25th International Congress of the Aeronautical Sciences (ICAS)*, Hamburg, Germany, September 3-8, 2006.

[13] Federal Aviation Administration, "TFM Training," URL: https://tfmlearning.faa.gov/tfm-training.html [retrieved 5 April 2022].

[14] Sridhar, B., and Chatterji, G. B., "Airspace Systems Technologies—Overview and Opportunities," Vickerman, R. (eds.), *International Encyclopedia of Transportation*, Elsevier Ltd., vol. 4, 2021, pp. 363-379.

[15] International Civil Aviation Organization, "Global Air Traffic Management Operational Concept," Doc 9854, First Edition, 2005.

[16] International Civil Aviation Organization, "Manual on Remotely Piloted Aircraft Systems (RPAS)," Doc 10019, 2015.

[17] Federal Aviation Administration, "Concept of Operations Unmanned Aircraft System (UAS) Traffic Management (UTM)," Version 2.0, March 2, 2020.

[18] Federal Aviation Administration, "Concept of Operations Urban Air Mobility (UAM)," Version 1.0, June 26, 2020.

[19] Paielli, R. A., Erzberger, H., Chiu, D., and Heere, K. R, "Tactical Conflict Alerting Aid for Air Traffic Controllers," Journal of Guidance, Control, and Dynamics, vol. 32, no. 1, January-February, 2009.

[20] Federal Aviation Administration, "Introduction to TCAS II," Version 7.1, February 28, 2011.

[21] Department of Defense, "Systems Engineering Fundamentals," Defense Acquisition University Press, Fort Belvoir, Virginia, 22060-5565, January 2001.

[22] Cole Jr., E. L., "Functional Analysis: A System Conceptual Design Tool," *IEEE Transactions on Aerospace and Electronic Systems*, Vol. 34, No. 2, April 1998, pp. 354-365.