Bowtie Analysis of the Effects of Unmanned Aircraft on Air Traffic Control

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Within the aviation domain, there is a growing industry demand to develop and integrate remotely piloted operations into the National Airspace System. However, it is not yet well understood how the integration of unmanned aircraft with impact air traffic control, and specifically, the air traffic controllers who are at the sharp end of this safety critical system. This research presented in this paper aimed to begin to address this gap in understanding by identifying and exploring potential hazards associated with introducing Unmanned Aircraft into the national airspace system, and identify possible mitigations to reduce identified risks. A bowtie risk analysis methodology was used to identify and analyze hazards. A focus-group format discussion was conducted with nine subject matter experts as participants. Findings identified five areas of potential risk, each associated with multiple hazards. Mitigations for each hazard are reported. Findings have essential implications for the safe and efficient integration of unmanned aircraft into the national airspace.

I. Nomenclature

ATC = Air traffic control
ATCO = Air traffic controller
C2 = Command and control
CTAF = Common traffic advisory frequency
DAA = Detect and avoid
GCS = Ground control station

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GA = General aviation
ICAO = International Civil Aviation Organization
IFR = Instrument flight rules
LL = Lost link
MOPs = Minimum Operational Performance Standards
NAS = National airspace system
SME = Subject manner expert
UA = Unmanned aircraft
UAS = Unmanned aircraft system
VFR = Visual flight rules

II. Introduction

WITHIN the aviation domain, there is currently a growing industry demand to develop and integrate remotely piloted operations into the National Airspace System (NAS). One of the specific areas of demand is remotely piloted cargo operations, due to the potential efficiency-related commercial benefits for airspace users. Across the last decade, research has been conducted to take steps towards meeting this growing demand. For example, NASA's Unmanned Aircraft Systems Integration in the NAS (UAS-NAS) project conducted progressively advanced concept testing and experimentation of remotely piloted operations across seven years, from 2012-2019. During this time, six flight tests (FT) were conducted. FT5, conducted in 2018, demonstrated a breakthrough beyond-visual-line-of-sight operation without a safety chase vehicle [1]. Human in the loop simulations were conducted on foundational principles to facilitate the reality of unmanned operations in the NAS, such as detect and avoid (DAA) systems [2-5] and command and control link communication systems [6], with findings becoming the basis for the RTCA's minimum operational performance standards (MOPS). This foundational research has supported the reality of introducing remotely piloted cargo aircraft into the NAS. However, the majority of the research efforts in this domain have dominantly focused on technology-related areas that are necessary to facilitate the feasibility of remotely piloted operations. A so-far understudied area is the integration of unmanned aircraft (UA) in the NAS, both safely and efficiently with current-day Air Traffic Management (ATM) operations.

An especially critical area of consideration is the potential impact of UA integration on current-day air traffic control (ATC) operations, and those at the sharp end of this safety critical system, the air traffic controllers (ATCOs). ATCOs are responsible for the safety and efficiency of all air traffic. As such, it is essential that ATCOs maintain a consistently excellent standard of human performance. New entrants in the NAS, with associated new technologies, service needs and operations, have the potential to influence operational demands and ways of working for ATCOs, as well as performance-influencing factors that are known to negatively affect ATCO performance, such as workload, Situation Awareness (SA) and fatigue [7]. It is therefore essential that the potential effects and implications of UA integration for ATC are identified, and where appropriate, mitigated, in order to support safe and efficient UA integration into civilian airspace.

The research presented in this paper begins to address the current gap in understanding of the impact of UA integration into the NAS on ATC and ATCOs. The objective of this research was to gain operationally valid information regarding potential hazards associated with introducing UAs into the NAS, specifically in relation to ATCOs, and identify possible mitigations to reduce identified risks. To achieve this objective, the research had several aims. First, the study aimed to identify the areas of potential difference to the current-day ATC operation as a result of UA integration (based on existing understanding and documentation of UA type, performance and technology). Second, the research aimed to gain insight into whether these differences had the potential to result in hazards or risk to ATCOs and the ATC domain, and identify the specific potential impacts for ATCOs. Finally, the research aimed to propose potential mitigations to identified risk, facilitating the safe and efficient integration of UA into the NAS, whilst reducing the potential impact to both the ATCOs and the wider ATC system.

III. Method

A. Design

To address the research aims, a bowtie risk assessment process was selected as the research methodology. The bowtie methodology is an established process for qualitative risk identification and has been applied in both academia and industry [8, 9]. The analysis is popular in the aviation domain; the International Civil Aviation Organization (ICAO) has published guidance for applying the bowtie method in aviation domains, and air navigation service providers (ANSPs) such as the Federal Aviation Administration (FAA) have documented use of the method for operational risk assessment [10].

The bowtie methodology is a structured process that facilitates the investigation of sequences between hazards, outcomes and mitigations. The analysis is usually grounded in subject matter expertise [11], supporting operational validity, and can be updated as new information becomes available [12]. In the present study, a bowtie analysis was conducted (see Section III.B.) and subsequently discussed during a five-day, knowledge-elicitation activity using a focus group format, conducted in August 2020. A total of nine subject matter experts (SMEs) participated, including six ATCOs, two Remote Pilots (RPs), and one commercial (airline) pilot. Discussion was focused on areas of ATC operations and ATCO tasks that may be affected by UA integration in the NAS. The activity was conducted via an online, teleconference platform and discussion sessions were recorded via the teleconference software.

B. Bowtie Analysis Development

1. *Predicted Areas of Change to the Current ATC System*

First, potential changes were identified through a document review exercise and operational knowledge from in-house SMEs, including pilots and former ATCs. The aims of the document review exercise were to increase understanding of the scope of changes to current-day ATM operations as a result of UA operations and identify knowledge so far on potential impacts on ATC as well as other airspace users. The use of existing documentation enabled the analysis to have a current, evidence-based foundation, again contributing to operational validity and relevance to the domain. Once relevant documents were identified, documents were reviewed by the research team, and relevant information was recorded for later use. [13-18] are examples of included documents. Documents were categorized into 5 main areas:

i. Current-day ATC operations
ii. Current-day air cargo operations regulations and policies
iii. Current MOPs for UAs in the NAS
iv. Current MOPs for Detect and Avoid (DAA) in the NAS
v. Command and control link between RP and ATC, including communication links.

As a result of the review, several hazards were identified to the current ATC system that could potentially occur from the integration of UA into the NAS, across 5 main topic areas (See section IV).

2. *Causes of Hazards*

With support from in-house SMEs, command and control link specialists and human factors researchers, causes of the hazards were identified.

3. *Hazard Outcome Identification*

Outcomes of the hazards were subsequently listed, based on previous experience from in-house SMEs as well as human factors literature.

4. *Mitigations*

Mitigations to hazards and to hazard outcomes were identified. Mitigations can be *claimed* , in that they already exist in the system to prevent or reduce the impact of the hazard or outcome; alternatively, mitigations can be *proposed*, meaning that the suggested mitigations don't currently exist in system, but could be integrated in the future.[7]

Second, a focus group format was then utilized where nine professional aviation SMEs were invited as participants to further develop and verify the analysis.

C. Analysis Scope and Assumptions

The Bowtie Analysis focused dominantly on human factors issues in relation to ATCOs. The RP's role was explored to the extent that it facilitated understanding of the impact on ATCOs. The workshop focused on both nominal operations as well as contingency operations. All domestic ATC positions were included in analysis (tower, approach and enroute). Consideration was also given to Class A/E Enroute, and Class B/C/D tower. Airport surface operations of the flight were not included for analysis due to the lack of sufficient information. UA's ground control

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[7] An optional 'step 5' qualitative risk assessment step can be completed on the collected data. The risk assessment takes into consideration the estimated frequency of the hazard (based on current hazard occurrences), the severity of the outcome and the probability of the outcome. This step is mentioned for completeness, but will not be discussed further in this paper.

station (GCS) design and technology were not included for analysis. Security of data was considered out of scope for this workshop. Aviation operators' roles outside of ATCOs and RPs were excluded from analysis, such as dispatchers, Traffic Management Units (TMU), Flight Service Stations, and ground support.

The following assumptions were declared to provide a context for the analysis. The UA was assumed to be similar to the ATR-42, a regional cargo aircraft commonly flown by commercial aviation carriers. The UA air cargo flight was assumed to typically take off from, or land at, a Class D airport (i.e., a smaller airport with an operating airport tower) or a Class E or G airport (i.e., a non-towered airport, i.e., an airport without an operating airport tower), and fly through Class A, B, C, E, or G airspace. Standard equipage assumptions included:

- Doppler radar
- High-resolution cameras
- Flight Management System
- Ground Proximity Warning System
- DAA System capability as specified in [16]

D. Participants

A total of nine SMEs participated in the bow tie analysis focus group discussions, consisting of six ATCOs, one Commercial Pilot and two RPs. All ATCO participants were Certified Professional Controllers with total certification years ranging from 17 to 31 years (M = 27.33, SD = 5.16). Of the ATCO's, two had Tower experience, two had TRACON experience and three had Enroute experience. RP's had a combined 6200 hours of UA experience flying General Atomics Predator (MQ-1, MQ-1B) and General Atomics Reaper (MQ-9, MQ-9A). The first RP had a Commercial Pilot license with instrument and multi-engine ratings and a combined 800 UA and manned flight hours in the NAS. The second RP had Commercial and Private licenses with instrument rating and a combined 7000 UA and manned flight hours in the NAS. The commercial pilot had 9450 total flight hours, ATP license with instrument and multi-engine aircraft ratings and IFR and night flight currency. In addition, this pilot was a licensed certified flight instructor for instrument and multi-engine aircraft.

E. Procedure

Due to the public-health situation at the time of the study, the bowtie analysis method was performed via an online, teleconferencing platform. Participants received a package of materials one week prior to the beginning of the analysis workshop with instructions on how to join and a research brief. Five days of discussions were held, from Monday through Friday, running from 8am to 3pm daily. The initial morning session focused on a brief on the concepts to be discussed and participant training. The remaining sessions engaged the participants in discussions led by the initial analysis. Participants were first introduced to a topic, and then each hazard was discussed. For each hazard, the causes, outcomes and mitigations were discussed as a group and modifications were recorded, as well as additional hazards. Throughout the week, the researchers and the participants talked through several scenarios of what outcomes might be possible, even if not necessarily likely, as a result of integrating UA cargo aircraft into the NAS. Once the process of hazard and outcome identification was complete, the discussion turned to identification of claimed (i.e., existing) or proposed mitigations. The study accumulated 27 hours of discussion, or about 5.5 hours a day.

F. Strategy of Analysis

Thematic analysis was selected as the analysis strategy. In line with the thematic analysis procedure the transcripts were read through, and elements of participant responses that were related to the aims of the study were identified. The transcripts were then re-read with the aim of categorizing the identified elements into emerging themes. No individually identifiable information of the participants was stored in the transcription to ensure anonymity.

IV. Results

Five areas of potential risk were identified during the bowtie analysis preparation (see section III.B.), and subsequently discussed in the focus group sessions:

i. Latencies in Communication and UA maneuvers
ii. Loss of command and control (C2) link
iii. UA interactions with VFR aircraft
iv. DAA
v. Airport-Specific Hazards (Controlled and Uncontrolled Airports)

Each area was associated with several hazards. The following results section is divided according to these five areas; within each section, a review of the associated hazards, causes, outcomes and mitigations are provided. Due to the large amount of data collected, only the selected hazards that received the most discussion, as well as those that participants reported to create possible safety-related concerns, are presented.

A. Latencies in Communication and UA Maneuvers

UAs are controlled via GCS using either terrestrial or satellite C2 link system. In accordance with current day understanding [16], the analysis assumed that these links would be used to transfer data between the RP and UA, as well as verbal communications between the RP and ATCOs. Each type of link has a specific delay associated (including radio communications) [18]. Local, terrestrial links (such as C band) are used when the UA is in line of sight of the GCS, and the delay is documented to be 135-225ms [18]. RP participants agreed with this and confirmed in their experience the delay on average to be approximately 215ms one-way. When the UA is beyond line of sight, satellite-based links (such as Ku band) are utilized, which are associated with a documented 374-720ms one way [18]. Again, RP participants agreed with the documentation and stated that they had both consistently experienced a 1.5 – 2 second total delay.

The potential impact on ATCOs of utilizing data links for both control of the UA and verbal communication compared to manned aircraft was discussed for nominal day-to-day operations. Two hazards were identified: (1) Increased verbal communication latency between RP and ATCO compared to current day manned operations; (2) Increased latency in UA response time to ATCO instruction compared to manned aircraft.

1. Hazard 1: Increased Verbal Communication Latency Between RP and ATCO

RPs confirmed that the hazard of increased communication latency with ATC compared to manned operations existed in the operation, and that they had both personally experienced the delay when using satellite link. Satellite links were reported to be sensitive to environment and terrain, resulting in potential additional delay. Delay when using terrestrial links was noted by RPs to be perceptible, but without impact to operations.

Participants identified potential outcomes of the longer satellite link delay on ATC operations. First, it was identified that RPs can have reduced opportunity to communicate with ATC; RP participants shared their experience of not being able to call ATC in a timely manner in congested environments. Although the RP would start a transmission as per manned operations, other pilots would also begin a transmission during the period of delay, increasing the frequency of blocked transmissions so that ATCOs do not hear either message. One RPs estimated that, on average, one in five radio calls were blocked by a manned aircraft. ATCOs reported that in busy or complex environments, transmission delay and blocked transmissions had several important outcomes for the ATC operation, including ATCOs losing time to resolve the blocked transmissions, increased workload, potential for increased frequency of overload, and degradation of situation awareness (SA). In lower workload situations, ATCOs reported that the transmission delay could be absorbed with minimal impact to operations. ATCOs also described a potential increase of missed readback frequency. A strategy in congested traffic areas is to inform the pilots that no readback is required in order to save time. Although it was also acknowledged that this was not in line with correct procedure, it was seen as sometimes the only option to prevent losing SA of the traffic. ATCOs suggested that with the delay in communications with UA, the technique may be likely to be used more frequently to manage workload.

2. Hazard 2: UA Response Time Latency Longer Compared to Manned Aircraft

The potential for a delay in the UA responding to RP instructions was also identified as a hazard. In manned operations, the usual task flow for pilots to respond to an ATC instruction is to receive the communication, readback, and input the instruction into the aircraft flight management system. The task flow for RPs responding to ATC is similar, although with one additional step, and delays in the task flow; The RP will receive a transmission after a small delay, readback (with an additional delay), input the instruction at the GCS, instruction is sent to UA via C2 link system, UA receives the instruction and maneuvers. In addition to the workflow-related delays, participants suggested that RPs may be slower to respond than manned aircraft due to the potential of competing duties or distractions (such as a supervisor talking to the RP in the GCS) and different input methods compared to manned aircraft.

Participants reported that potential outcomes of this hazard were similar to those documented in Hazard 1 with the addition that the ATCOs' plan may not be implemented as expected due to the maneuver delay, resulting in the potential for increased workload and reduced SA.

Proposed mitigations were similar for both hazards due to the similarity of causes and outcomes. Mitigations were grouped into the categories of technology, training, procedures and future research. Technology-related mitigations included technology development to increase link speed and reliability, as well as solutions to extend the situations in which UAs can use terrestrial links as opposed to satellite links, such as additional antenna placements. Another suggestion was that airports used by UAs have terrestrial link capabilities to minimize delay in this time-critical control phase and facilitate complex procedures during landing and takeoff. Another proposed mitigation was a UA-specific identifier that could be integrated into the UA's data tag. All ATCO participants stated strongly that a unique identifier for UAs was essential to minimizing the impact of UAs on ATC. Controllers can adapt strategies to meet user needs and ensure the safety and efficiency of air traffic. However, to do this, ATCOs need to be given relevant information about an airspace user before it enters the ATCOs' sector. Examples in current day airspace include an identifier of aircraft weight class (e.g., heavy), and whether an aircraft is IFR or VFR. Training-based mitigations for ATCOs were also proposed, focusing on the performance of UAs and the differences to manned aircraft (such as communication delay) to enable ATCOs to provide the best service to all airspace users. Participants also suggested future research topics including link bandwidth and reliability, validation that the mitigated delay is acceptable to ATCOs, and exploration of a UA identifier placement that is acceptable to ATCOs.

B. Loss Of Command and Control (C2) Link

Prior to discussing hazards, RP participants emphasized that a distinction should be made between several types of non-optimal C2 link, as opposed to just considering the complete C2 link failure. Table 1 lists the type of non-optimal C2 links as specified by participants.

Table 1 Types of non-optimal C2 link and associated definitions, as reported by participants

Type	Definition
Total loss	Total loss of C2 link with the UA. Loss of control.
Degraded link	Relates to any condition with a non-optimal signal connection, but without total loss.
Partial lost link	Either the upload or download portion of the C2 link is non-functional.
Intermittent link	Loss of link and recovery of link that occur in succession

Several hazards were identified during discussions on the potential failure of the C2 link to the UA. Loss of voice communication between RP and ATC was discussed as a potential hazard, although participants reported that as the RP could instead use a landline to contact ATCO, the hazard was not a concern. Four hazards with the greatest potential impact on ATC (based on participant opinion) are discussed in the following section:

1. Total loss of C2 link (and associated RP alerting)
2. Inappropriate lost link (LL) contingency plan for airspace conditions
3. Partial LL
4. Recurrent LL and recovery

1. Hazard 1: Total Loss of C2 Link

Total loss of C2 link was reported to have several causes. Although satellite-based links were more susceptible to these causes, terrestrial links were also reported to be affected. Causes could be environmental, such as weather, solar storms, or surrounding terrain creating interference, and technological, including damaged antennas and UA or GCS power outage. Importantly, the cause of C2 failure impacted the likelihood of C2 recovery. For example, causes such as an antenna blockage would be likely to result in a temporary loss of C2, whereas an antenna failure would create a long-term LL.

The potential outcomes of a total loss of C2 link ranged from relatively minor, e.g., increased ATCO workload although not beyond levels experienced in current day operations, to more severe, e.g., potential for a loss of separation event or even collision. A particular concern raised by participants was the lack of responsiveness of the UA after a loss of link, specifically, that the UA would fly on the programmed contingency route regardless of obstructions (e.g. another aircraft) or environmental conditions (e.g. thunderstorms), with risk to both UA and other aircraft. This outcome was viewed as an even greater concern in airspace with reduced control services, including Class E and G airspace which permit VFR aircraft that is not controlled by ATCO. In Class A airspace, UAs could be more easily protected from other traffic with ATCOs able to separate other IFR traffic around the UA as needed. In addition, ATCO participants reported that the impact of LL was likely to be less in Enroute sectors due to the larger airspace that ATCOs had available. In contrast, participants suggested that the impact of LL in TRACON and Tower environments could be more severe, due to more complex traffic movements, smaller sectors and tighter separation minima.

Mitigations to prevent the LL were discussed and focused on technology-based solutions to improve the reliability of links or expand the areas where the UA had access to terrestrial links. Mitigations to reduce the impact of the potential risk were also discussed. ATCOs reported that it was essential to have immediate access to the planned contingency route of the UA to be able to quickly and effectively plan other traffic around the UA. Concerns regarding risk in Class E and G environments remained, although suggestions to try and minimize the identified risks included issuing an advisory of a LL UA on the Guard frequency, as well as educational outreach to general aviation (GA) users of the airspace via flight schools. A stronger mitigation was suggested to physically separate UAs from other NAS traffic around small airports. UA-specific hubs for landing and takeoff was perceived to offer increased protection for UAs in environments without ATC services. Another suggested alternative was to close towers to VFR traffic if a UA was landing during a LL event, although it was acknowledged that this would be likely to have a negative impact on airport efficiency. Technology-related mitigations included a LL automatic squawk code of 7400, as well as a unique UA identifier, so that ATCOs were aware of the LL potential and develop effective backup plans accordingly. Without prior knowledge of the potential for a LL event, ATCOs described that they would be forced to be more reactive to the event, with potential negative effects on effectiveness of the response as well as a significant workload increase.

A related discussion emerged regarding the alerting of LL to the RP in a timely and salient manner, to ensure that the RP knew that the link was lost. RPs fed back that alerting of a complete LL was not a priority concern however, as other cues of LL, such as lost video or instrument feeds, were available. However, design of LL alerts in line with human factors principles and user evaluation feedback was agreed to be beneficial.

2. Hazard 2: Inappropriate LL Contingency Plan for Airspace Conditions

The LL flight profile, otherwise known as a contingency route or contingency flight plan, is a pre-programmed route that the UA will fly automatically if link is lost. Usually, the LL flight plan is similar to the approved flight plan (with the exception of including the potential of loitering points near the destination airport with terrestrial links). Although both ATCOs and commercial pilot agreed that continuing the planned flight plan was the most predictable, and therefore, acceptable option for a LL contingency plan, concern was expressed that the planned route may no longer be appropriate to current sector or route conditions, due to weather, existing aircraft emergencies, or other dynamic airspace situations. Safety-related outcomes were identified, such as the potential for damage or loss of the UA (e.g. flying through a thunderstorm), as well as potential loss of separation or even collision with other traffic (such as in the case of an aircraft emergency which happens to be on the flight path of the UA). As a mitigation for these concerns, RPs shared that for military missions, the contingency plan is updated dynamically by the RP during the time the link is functional. For example, if an instruction from ATCO diverts from the current flight plan, the RP will update the contingency plan so that if the UA lost link, it would fly to the waypoint cleared by ATC, and then deviate to get back on the route of the original flight plan. In addition, if weather cells were identified close to the UA, the RP would update the contingency plan to navigate around this weather cell and return to the flight plan route once clear of the cell. Although updating the contingency plan somewhat mitigated the concern of a non-dynamic LL flight plan, risk was also identified in updating the contingency plan, for example, an RP error when inputting new instructions. It is unclear if updating the LL contingency plan is planned for civilian UAS in the NAS. Further research is needed to explore best practice for updating the LL plan to account for dynamic changes in the airspace. Other proposed mitigations for consideration included procedures to specify weather thresholds that would trigger a UA to land at nearest airport, and procedures to ground the UA if weather conditions along route do not meet threshold.

3. Hazard 3: Partial LL

RP participants raised an important consideration that C2 link can be partially lost as well as completely lost. Partial LL was characterized as loss of either the uplink (GCS to UA) with an active downlink (UA to GCS), or loss of downlink but active uplink. Participants did not show concern for the scenario in which the uplink had failed but downlink was active. In this case, RPs would still receive information from the UA, although instructions could not be sent to the UA. Participants stated that this was similar to the complete LL except more information from the UA could be received. Participants suggested that procedures should specify that the downlink should also be manually severed in this situation so that the UA would start the LL profile. Of greater concern was the loss of downlink but an active uplink. Without a downlink, RPs receive no feedback from the UA, and appears the same as a complete LL. However, as the uplink is still active, the RP could give instructions to the UA in error without awareness of potentially severe consequences. Participants suggested that an alert designed specifically for this partial-LL scenario, as well as a procedure to severe the link to initiate the UA LL profile, would effectively mitigate this risk.

4. Hazard 4: Recurrent LL and Recovery

Recurrent C2 LL was confirmed by participants to be possible due to reoccurring and dynamic causes of LL such as weather and terrain. It was assumed, based on current military UA function, that C2 link would be restored automatically once available, which created the possibility of recurrent LL and recovery. Such LL-recovery oscillation was reported to have the potential to create a substantial impact on ATC, including added transmission congestion, distraction, increased workload, potential workload overload, and confusion of UA state, resulting in uncertainty of UA flight path and UA action upon reestablished link.

Directly related to this hazard was the concept of the pre-determined time threshold, otherwise known as 'arming time' or transaction expiration time [19] for initiating LL contingency plans. If this threshold was set too stringently (i.e., a short time between detecting LL and initiating the LL profile), the frequency of recurrent loss and recovery of link would increase. However, set too leniently and the profile may not execute in time to avoid a potential safety event such as a loss of standard separation between UA and other aircraft. Participants reported that it was critical that the arming time of the LL profile be further researched for operational validity and user (including ATCOs, commercial pilots and RPs) acceptance. In addition, ATCOs stated that the arming time threshold should be modified to the airspace that UA was operating in at the time. During Enroute operations, again because of larger sectors and more available airspace, ATCOs reported that the arming time could feasibly be longer; participants felt that UAs could take some time to reestablish the link without significantly increasing risk as long as the UA is kept to the cleared flight route. Conversely, TRACON and tower controllers emphasized the importance of a shorter arming time in these flight phases, as the ATCOs had less airspace and flexibility compared to Enroute operations, and a higher likelihood of conflict with other maneuvering aircraft.

C. UA Interactions with VFR Aircraft

Operating under visual flight rules (VFR) reduces the level of positive control that ATCOs can offer for these aircraft. Instead, the pilot-in-command (PIC) is primarily responsible for meeting separation minima via the principle of 'see-and-avoid'. The mix of UA and VFR aircraft without positive control in the same airspace was believed to raise potential hazards.

The hazards and associated outcomes that participants discussed were dependent on the class of airspace under consideration. Airspace classes A does not permit use by VFR aircraft, removing this class from further discussion. Participants were also less concerned with Class B and C airspace, as IFR (e.g. UA) traffic would be separated from VFR aircraft by ATC. Participants perceived that the risk for IFR-VFR interactions was higher in Class D and E airspace as IFR aircraft were not explicitly separated from VFR traffic (although were given traffic advisories, ATCO's workload-permitting), and hazards were of greatest concern in Class G and non-towered airspace, where VFR aircraft is not required to obtain ATC clearances or to be under positive control of ATC. Airspace Classes D, E and G were therefore selected as context for discussing hazards. Two hazards were raised by participants. Non-towered airspace is discussed separately (see section IV. E).

1. Hazard 1: Reduced RP Visual Information in VFR Interaction Compared to Current Day Operations

Even though UAs are expected (at least in the near term) to fly under IFR, there is a requirement of a 'see and avoid' capability in relation to VFR aircraft. As the RP is not co-located with the UA, the RP will be reliant on video streams and/or other technologies that can provide an equivalent replacement to the visual information open to manned pilots. However, there are currently sparse requirements for minimum UA equipages that provide visual information (such as camera field of view, resolution, etc.). Several safety critical outcomes were identified as a potential result of a lack of visual or visual-equivalent information of the surrounding aircraft, including collision, loss of standard separation, and inadequate RP SA. Specific to class E environments, participants raised the consideration of operations without a transponder such as gliders or skydivers being 'seen' by UA aircraft. Several outcomes were also identified that were specific to Class D airspace, including reduced efficiency and throughput at the tower as a result of greater separation requirements for IFR compared to VFR aircraft, and a potential increase of go-arounds resulting from UAs missing arrival slots. An existing mitigation was acknowledged to be the detect and avoid (DAA) system that is currently under development [16]. This system aims to replace the 'see and avoid' concept of manned aircraft by identifying 'targets' (such as other aircraft) and presenting these targets to the RP in relation to the UA. MOPs for the DAA system are in publication [16] although DAA currently remains in the research stages of development. Other possible mitigations that were suggested included a minimum set of requirements for a visual feed from a camera, to be used around tower environments, and modified procedures for UAs landing at a Class D airport, specific to runway configurations and flying a tower pattern.

2. Hazard 2. VFR Aircraft Unfamiliar with IFR Operations

A second hazard was identified that pilots of VFR aircraft may not be familiar with UA IFR operations, and may respond inappropriately or unknowingly against regulations. Although it was determined that this was not a primary concern, suggestions were raised to conduct outreach and pilot education at VFR airports in respect to UA operations.

D. Detect and Avoid (DAA)

DAA system is proposed for use on all UAs. DAA provides traffic information, including vector and altitude, in relation to the UA. Information is displayed to the RP at the GCS. DAA alerts RPs to traffic that creates a potential conflict and provides resolution guidance to the RP. Three classes of DAA system have been conceptualized, starting with Class 1, progressing in technology capability and integration to a Class 3 system (please see [16] for detailed information). As per current MOPS [16], Class 1 DAA equipment, as defined by [16] has been defined as a minimum equipage requirement [16, 20] for UAs. Although it is acknowledged that other, more sophisticated Classes of DAA system are envisaged for the future, the current analysis focused on the minimum equipage requirement of a Class 1 DAA system. Hazards were identified centered on the target detection and resolution guidance of the DAA system.

1. Hazard 1: Target Detection Failure

DAA technology relies on several sensors and cameras to detect targets. However, there are certain ‘blind spots’ in the DAA system where targets cannot be detected, resulting in a lack of alerting of conflicting aircraft and associated guidance. This was a particular concern to participants, and several safety-related outcomes were documented, including collision and loss of standard separation. Another cause of target detection failure was identified for targets without transponders, such as gliders and parachutes, also resulting in potentially safety critical outcomes. Mitigations focused on technological solutions, such as increased and improved placement of sensors and cameras to minimize blind spots.

2. Hazard 2: DAA Guidance Inappropriate to Airspace

Once a target is identified, the DAA system provides guidance to the RP in the form of ‘bands’ of airspace the pilot could use to turn away from the conflict. These bands of airspace reflect areas the DAA system has not detected further conflicts with targets. However, at the time of discussion, DAA did not take into account of risks such as terrain or weather, creating the possibility that the guidance is not feasible or accurately represents reality. Again, this was a concern for participants, who raised the possibility of safety critical outcomes. A discussion point focused on the DAA guidance was raised. As PICs, RP had ultimate responsibility to ensure the resolution was safe and effective prior to using the guidance, much like in a see-and-avoid situation. However, participants agreed that inaccurate guidance could be misleading, and affect the trust of the RP in the DAA system. Mitigations were again technology-focused, including integration of available sensors such as terrain. In addition, RP training on the limitations of the technology, and increasing transparency of resolution guidance calculations to support RP’s decision making were proposed.

3. Hazard 3: RP Over-Reliance on DAA Guidance

DAA-related hazards were not only technology-focused. A potential hazard was identified that was common to many automated guidance systems, specifically, that RPs could become reliant on the DAA system, including DAA resolution guidance, resulting in complacency. It was reported by RP that this risk was especially relevant to low workload situations, in which the RP may not be completely engaged with the task. Mitigations focused on human factors principles for combatting overreliance and trust in technology, including designing for increasing transparency of the system and providing training on system limitations.

E. Airport-Specific Hazards (Controlled and Uncontrolled Airports)

Hazards were identified that were specific to the airport environment. Hazards were the same for controlled airport and uncontrolled airport (e.g., non-towered airport operated with common traffic advisory frequency or Unicom) environments, although mitigations for each area were tailored to the concerns of each environment. Three main hazards were identified in the tower environment:

1. Inadequate RP SA of takeoff conditions
2. Inadequate RP SA of landing conditions
3. Inadequate awareness of bird strike, wind shear, or other off nominal activity

All hazards were associated with a root cause of limited visual, or visual-equivalent, information compared to manned aircraft. Exacerbating the issue is that current standards for visual - or visual-equivalency- information for UAs are insufficiently defined as a replacement for an in-the-cockpit/out-the-window view, particularly in respect of defining criteria such as bandwidth, signal strength, resolution and field of view. Contributing to the hazards is also a lack of haptic feedback compared to manned aircraft, further reducing the information available to the RP about the tower environment.

1. Hazard 1. Inadequate RP SA of Takeoff Conditions

A hazard was identified that RPs may have an inadequate SA of the airport environment, specific to takeoff conditions. Examples of safety critical outcomes included not perceiving obstructions during taxi or takeoff, or runway incursions, and more generally, a decision to take off in unsafe conditions. However, participants noted that in Class C and D airports, ATCOs retain the responsibility of separating IFR (i.e., UA) aircraft, and so the risk associated with this hazard was perceived to be lower than in uncontrolled airport which do not have these protections. Another consideration was the potential lack of SA specific to environmental conditions. Examples included wind shear events, thunderstorms or icing conditions that could create safety concerns for the UA. It was acknowledged that weather information services such as the automatic terminal information service (ATIS) would support RP awareness, although potentially not to the extent of being in an aircraft cockpit. Mitigations that were appropriate for both controlled and uncontrolled airport environments were suggested by participants. Detailed go/no-go criteria that was tailored to the UA (e.g., potentially with more reliance on instrumentation read-outs or other mechanisms to replace visual inputs) was viewed as an important mitigation. Technology-based suggestions included minimum requirements for visual information, such as UA-mounted cameras (including minimum requirements of placement, field of view and resolution), airport-surface cameras, and adaption of the DAA system to surface environments. ATCOs re-emphasized that a UA identifier would also facilitate ATCOs in effectively controlling to meet the needs of the UA in controlled airport environments. Additional mitigations included the retraining and use of company ground crew that were co-located with UAs at key airports in order to report this information back to the RP. This mitigation was viewed favorably by participants, especially in relation to an uncontrolled airport environment. The feasibility of mitigations was discussed in terms of resources and likelihood of implementation, although it was decided that suggestions should not be limited by these considerations at during this exploration phase.

2. Hazard 2. Inadequate RP SA of Landing Conditions

A related hazard was identified as inadequate SA of landing conditions. Although resulting from the same causes as documented above ('inadequate RP SA of takeoff conditions'), separate outcomes were listed for the landing portion of the flight compared to takeoff. Participants reported that the possibility of landing in unsafe conditions was somewhat mitigated in controlled airport environments with operational tower. Thus, uncontrolled airport environments are again highlighted as the primary concern. Participants also suggested that go-arounds may increase in frequency due to the potential for delayed or reduced detection of unsafe landing conditions, particularly at uncontrolled airports. Mitigations were similar to those discussed in the takeoff scenario, although an additional mitigation was proposed that UA aircraft may have a visible, physical identifier, such as a specific light or tail marker, to support the awareness of other pilots in the uncontrolled airport environment of the presence of a UA. To further increase awareness of manned pilots of UA operations in the area, signage at the airport and information on ATIS and/or Notice to Airmen (NOTAM) were also suggested.

3. Hazard 3. Inadequate Situation Awareness of Off-Nominal Events

A further hazard at the airport environment was reduced awareness of RPs for off-nominal events that, for manned aircraft, would be detected through haptic feedback, sounds, or proprioception. Examples included bird-strike, wind-shear events, microbursts, and other off-nominal symptoms such as hearing something 'wrong' with the engine. Outcomes from delayed or missed detection of off-nominal events ranged in severity, from RP confusion and distraction to damage to, or loss of, the UA. A particular concern for participants was that corrective or recovery actions may be needed, such as in the case of wind shear or microburst events. However, these would be delayed or not conducted due to non-detection, increasing the potential of more severe outcomes. Participants acknowledged there were several existing mitigations that could address these concerns. Examples included that RPs would still have access to instrumentation. Several off nominal events, such as windshear or microbursts, could be detected through instrument reading changes. In addition, several advisory systems could support the awareness of the RP, including ATIS, pilot reports (PIREPS) and the company communication line. Although participants agreed that the mitigations would be beneficial, concern remained about the late, or no, detection of an event, even with available instrumentation access. Mitigations focused heavily on training for RP, focusing specifically on the detection of potential off-nominal events through instrumentation cues alone. Other mitigations included visual aids such as UA- or ground-located cameras, and tools to achieve information equivalency to pilots in a manned aircraft.

V. Discussion

The presented findings identified potential hazards, causes, outcomes and mitigations, judged from SMEs' past experience, that may result from the future integration of UA into the NAS. These findings are an important step towards addressing the current research gap in understanding potential risks of UA integration, and associated mitigations to reduce or eliminate these risks, prior to operational implementation. Hazards were identified for all airborne phases of flight, and mitigations provided. Throughout discussions, the following themes of moderators of risk emerged repeatedly, and it became apparent that the frequency of hazards, as well as the severity of outcomes, were affected by the context of the situation.

Airspace class: Whilst several hazards were applicable to all classes of airspace, several hazards and outcomes were perceived by participants to pose increased risk in Class D, E and G. Reasons for this perception included a great mix of air traffic, with varying equipages, pilot experience level, and varying intensions, all leading to much less predictability than in Class A, B, and C environments. In addition, the reduction of positive control in airspace classes D, E also meant that ATCOs had less ability to ensure UA separation from other airspace users. It is suggested that mitigations tailored to addressing the unpredictable nature of the environment are developed, and outreach to the GA community supports awareness of UA limitations.

Type of airspace: The severity of the impact of the identified outcomes were also described by participants to be dependent on airspace type. For example, in Enroute, more airspace often means that ATCOs have more time and flexibility to adapt to non-optimal events or situations. However, in tower and TRACON environments, airspace is often more congested, with time-critical maneuvers and complex traffic flows, resulting in less flexibility for ATCOs to manage unexpected events or aircraft needs. When examining hazards and outcomes, it is essential to take into account the different types of airspace as a moderator of the severity and probability of the hazards and outcomes. In addition, it is important that mitigations also take into account the context of the airspace to ensure effectiveness as well as operational validity.

Workload: Arguably, the most dominant moderator that was highlighted by participants was the current taskload and associated workload that was experienced by that ATCO at the time of a hazard occurrence. ATCOs expressed that the current traffic density and workload had the potential to influence the frequency of the hazard occurrence as well as the severity and probability of the associated outcomes. When exploring and prioritizing risk in future work, the context of occurrence is critical to take into account to gain an operationally valid understanding of the safety and efficiency impact to both the ATCOs and the wider ATC system.

ATCOs prevent and mitigate negative impact on the ATC system: ATCOs maintain system safety by identifying and responding to often unpredictable, dynamic events. The role of the ATCO in preventing or mitigating hazards and outcomes is essential and is demonstrated repeatedly in present-day air traffic operations. As a result, the more information that ATCOs have prior to a hazard occurring allows the ATCOs to prepare and develop backup plans for various situations. A key focus of mitigations should therefore be to ensure ATCOs have timely information available about the new entrants. Examples include a UA identifier in the data tag, and access to LL profiles. This helps increase the ATCOs' understanding of the current airspace and traffic situation and plan accordingly. This is demonstrated in the current environment, where aircraft have indicators for weight class due to differing needs.

A. Implications

1. *The Importance of Scenario and Environment Design in ATC Simulations*

One of the patterns identified in the findings was moderating conditions. Repeatedly, ATCOs noted that environmental factors, such as existing levels of workload and complexity, sector characteristics, airspace class and phase of flight, interact to determine the overall impact UA in the NAS has on ATC. One example is the effect of communication latencies on ATCOs. In a low traffic-volume, low complexity environment, with a large Enroute sector with minimal restrictions on use of the available airspace, and no weather or aircraft on vectors, the communication delay can be absorbed by the operation with minimum impacts to ATCO performance or the safety and efficiency of the ATC service. However, in a high traffic-volume, high complexity environment, in a small TRACON sector with not much flexibility in how to use the airspace, delay in communications would become more critical and impact the ATCO and potentially the safety and efficiency of the operation. The findings of this pattern in the data have substantial implications for human in the loop simulations. If data on the impacts on ATC of UAs integrated into the NAS is attempted to be captured in a simulation environment, no performance effects will be seen in optimal scenarios (e.g., low traffic, low complexity, large sector, no weather etc.) as ATCOs have enough time and flexibility to implement supportive control strategies to support the operation (such as increasing safety buffers, changing control strategy) to reduce workload. As shown in the data in this study, this result does not mean that UA in the NAS will not impact ATC, or risk will not be introduced to ATC operations. It simply means that the simulation scenario does not reflect the conditions where the impact will be unmanageable for ATCOs, and therefore, not sensitive enough to capture data on effects on ATCO performance and the operation. It may be possible to record increases in supportive strategy use, such as increase in safety buffers, but this can be difficult to identify in the data. It is therefore recommended that simulation designs consider a range of airspace and phase of control (tower, TRACON, enroute), including non-optimal situations (such as high traffic or weather issues) in order to increase the likelihood of capturing data on the impact of UA in the NAS on ATC, and the conditions that interact to increase the likelihood of that impact. This preliminary qualitative analysis indicates the areas that are most troublesome for specific hazard events.

2. Exploration of System Tolerance

Another pattern in the data was the need for validation of several new technologies to confirm equivalency (or better) with current day technologies (again, communication latencies are a good example). However, this raises an important question. Focus may shift to become a question of tolerance – what the ATM system can tolerate before safety or efficiency is compromised. If system tolerance is examined using simulations, it is again essential that a variety of scenario designs are used to develop an operationally valid understanding of system tolerance to ensure the same, and ideally better levels of efficiency and safety with the integration of UA in the NAS.

3. Concept of Operations (ConOps)

Throughout the workshop, new procedures, and modifications to existing procedures, were suggested as proposed mitigations to identified issues that could result in operational risk. Concept of operations development may use these findings, and additional future research, as a foundation for understanding the requirements to mitigate potential risk.

B. Future Research

Due to the foundational nature of the concept, much further research is needed. Throughout the workshop, areas of future research topics were identified that would contribute to enabling UAs in the NAS. Future research topics have been documented throughout the report, but for clarity, a selection of proposed research topics is summarized below. Several areas of future research were identified based on those topics that were outside the scope of this current analysis. The investigation of C2 link security will be essential to enable the reliable integration of UAs in the NAS. In addition, the potential influence of UAs in the NAS on other roles, such as dispatchers, should be examined. Surface movements, including pushback, taxi, and after landing were also not considered due to the limited information currently available regarding options for taxiing without visual capabilities. Research into surface movements is a vast area and is essential to support UA integration into the NAS.

Technology development was also a repeated focus for future research. Topics included the continued development of the DAA system, to address current issues including target detection ‘blind spots’ and not being functional below 400 feet. In addition, research to improve the reliability, or at least identify mitigations, of the satellite links was also recommended. Experimental simulation was proposed to explore ATCO acceptability of satellite-based links, incorporating several scenarios using different airspace classes and high-density high complexity traffic.

Continued research was also recommended to investigate the new role of the RP, to gain a more comprehensive understanding of the tasks and responsibilities of the RP, compared with manned aircraft. Further research should consider a task flow analysis of the RP role in comparison to manned-operations pilots to document differences (such as more activities to complete in a specific task flow), and gain insight into the potential impact for ATC of identified differences.

Looking toward the future, two areas of research were suggested to support further development of UA in the NAS. First, the future vision of multiple UAs to one RP has critical implications for ATC and the potential to introduce risk into the ATM system. Many issues identified in this report would be exacerbated by increased RP workload, potentially resulting from control of more than one UA. In order to facilitate and enable this future vision, research should focus on the investigation of the potential risks and mitigations resulting from multiple UA own ship by one RP. A second safety-critical consideration is the topic of autonomous action for the UA resulting from DAA guidance. It is possible for the technology, when receiving a warning alert, to respond autonomously without input from the RP or ATC. This has advantages, as should only be used to avoid collisions. However, the concept of uncontrolled maneuvers in the airspace has several legal implications as well as the need for a reliable and accurate DAA system. Future research should investigate the feasibility, acceptability, and legality of autonomous action of the UA.

Human-machine interaction (HMI) considerations specific to the RP and GCS were another area that was highlighted for future research. Currently, there is no standardization of control inputs for UAs; UAs can be piloted via stick and rudder, or even from a keyboard and mouse. Not only do these HMI considerations have an impact on potential error of the RP, but also has an impact on ATCOs, for example due to error or delay in entry. Future research should investigate the control inputs and HMI that supports optimal RP performance and consider creating guidance documents.

VI.Conclusion

The research presented in this paper aimed to contribute to understanding of the impact of UA integration into the NAS, with a specific focus on the effects on ATC and ATCOs. This aim was achieved through the application of a structured bow tie risk assessment method. Five primary areas of potential risk were identified, each associated with multiple hazards. The current work confirms that new hazards will be created with UA integration into the NAS, but also provides recommendations for addressing those hazards via mitigations. Further work should investigate other potential hazards in areas not covered by the current analysis. It is essential that further research also investigates the effectiveness of applied mitigations, prior to operational implementation in order to facilitate the safe and efficient integration of UAs into the NAS.

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