Unmanned Aircraft System Response to Air Traffic Control Clearances: Measured Response

Robert J. Shively, NASA Ames Research Center
Kim-Phuong L. Vu, California State University Long Beach
Timothy J. Buker, SAIC

In the National Airspace System (NAS), Air Traffic Control (ATC) expects aircraft to complete ATC clearances in a timely manner in order to maintain minimum separation between aircraft. The end-to-end response time for an aircraft to complete a clearance, as measured from the end of ATC instructing the pilot of the clearance to the just noticeable difference (JND) on the ATC display of the aircraft satisfying the clearance (i.e., initiation/completion of an altitude climb), can be referred to as measured response (MR). This MR is not quantified in Federal Aviation Administration (FAA) standards, regulations, or policy; however, as manned aircraft have developed along with the Air Traffic Management System, a shared understanding of reasonable and timely response has evolved. By contrast, the introduction of unmanned aircraft systems (UAS) into the NAS has highlighted this issue. This paper seeks to define MR and its components, and describe a methodology, with an example, that can be used to investigate it.

INTRODUCTION

In the National Airspace System (NAS), Air Traffic Control (ATC) expects aircraft to complete ATC clearances in a timely manner in order to maintain minimum separation between aircraft. The end-to-end response time for an aircraft to complete a clearance, which can be referred to as measured response (MR), is measured from the end of ATC instructing the pilot of the clearance to the just noticeable difference (JND) on the ATC display of the aircraft satisfying the clearance (i.e., initiation/completion of an altitude climb). This MR is not quantified in Federal Aviation Administration (FAA) standards, regulations, or policy. Rather, minimum separation standards set the parameters for which aircraft must perform to, and end-to-end response times that are acceptable to ATC are those that maintain separation.

In order to safely integrate unmanned aircraft systems (UAS) into the NAS, UAS must adhere to the same separation standards as manned aircraft and thus must be able to complete an ATC clearance in a timely manner. However, UAS are inherently different from manned aircraft in several aspects that affect end-to-end response time (see, e.g., Gawron, 1998; Merlin, 2009). For manned aircraft, the pilot is on board the aircraft and the control input is wired to the control surfaces and other systems of the aircraft. For UAS, the pilot is in a control station that is remote from the aircraft and the control input must travel wirelessly through the air or through a satellite relay, depending on the data link architecture, adding a delay not present with manned aircraft. The variable control delays can make the control of the UAS more difficult (Mouloua, Gilson, Kring, & Hancock, 2001).

For manned aircraft, separation is maintained, and thus response time is acceptable, as a result of decades of knowledge gained regarding airworthiness and operational standards: FAA standards for required communication performance sets maximum voice communication time from ATC to pilot (and vice-versa); FAA pilot training and certification requirements maintain consistent expertise in communication, decision-making, and piloting skills; FAA standards for the flight deck human-machine interface (HMI) ensures displays, controls, and alert and warning systems promote effective information processing and timely interaction with the HMI; Wired controls on board the aircraft ensure minimal time from pilot input to corresponding aircraft maneuvering; and known aircraft maneuvering performance allows ATC to project future position of aircraft. Required communication performance is assumed to be applicable to UAS; however, standards such as for UAS pilot training and the control station HMI have not been developed. The additional delay due to the data link, as well as the UAS maneuvering performance and operating characteristics must also be a factor in developing UAS standards (Blickensderfer, Buker, Luxion, Lyall, Neville, & Williams, 2012). For example, some UAS may not be able to fly as fast or climb as quickly as manned aircraft. This adds to the need to characterize current UAS response time in order to identify these performance differences and develop appropriate standards.

As previously discussed, FAA standards ensure acceptable response times for manned aircraft; however, those standards assume an on board pilot. Research must evaluate UAS response time to ATC clearances in order to better understand current UAS designs and operations in comparison to manned aircraft. These evaluations must quantify end-to-end response times with a subset of current UAS designs and data link architectures, and identify the design modifications that may reduce the response times to within ranges observed with manned aircraft.

To understand the end-to-end response time of both manned aircraft and UAS, one must first identify each time component. From the end of an ATC clearance instruction to the just noticeable difference (JND) on the ATC display of the end of the aircraft maneuver, the response time components are as shown in Figure 1 and described in the following list.

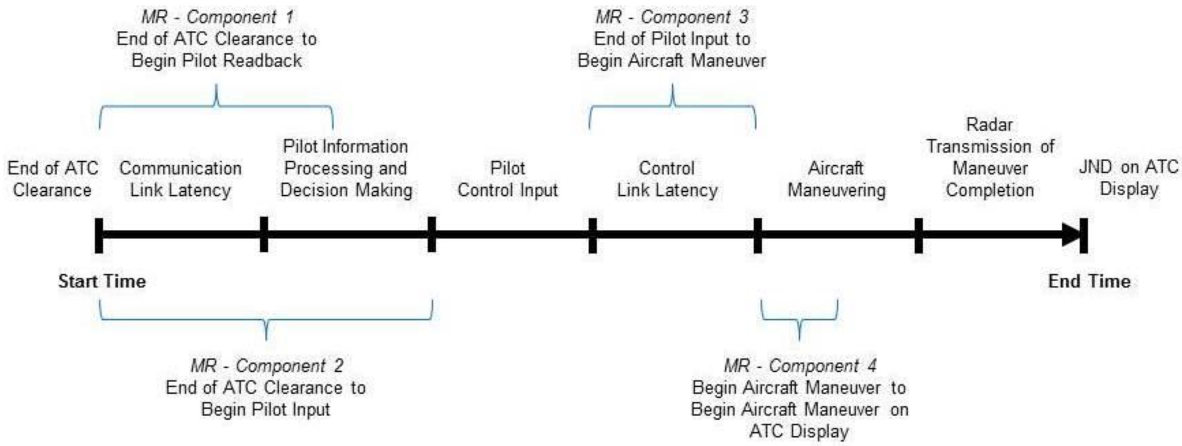

Figure 1. End-to-end response time, measured response, for completion of ATC clearances. Components measured in the present simulation are italicized above.

- Communication Link Latency: Time to transmit the clearance from ATC to the pilot.
- Pilot Information Processing and Decision Making: Time for the pilot to cognitively process the clearance, make a decision, and formulate an action plan.
- Pilot Control Input: Time for the pilot to interact with the human-machine interface and execute the input.
- Control Link Latency: Time to transmit the pilot input to the aircraft (wired transmission with manned aircraft and wireless transmission with UAS).
- Aircraft Maneuvering: Time for the aircraft to maneuver, measured from the beginning to the end of the maneuver.
- Radar Transmission of Maneuver Completion: Time to transmit the end of the aircraft maneuver, to appear as a JND on the ATC display.

The research described here evaluates the effect of ATC clearances on MR of UAS. In addition, pilot workload and ATC acceptability are measured. A human-in-the-loop (HITL) simulation was conducted because it allows measurement of measured response components outlined above.

METHOD

Participants

Fourteen certified pilots participated in the study. All pilots were males, and all but 3 reported being IFR rated. The pilots averaged 26.6 years of age (range 20 to 33 years), and had an average number of 1,205 flight hours (range 110 hrs to 4,500 hrs). Two, radar-certified air traffic controllers (ATCos), averaging 18 years of experience, also participated in the simulation.

Instruments and Simulation Environment

The simulation was run using the Multi UAV (unmanned aerial vehicle) Simulator (MUSIM), the Multiple Aircraft Control System (MACS), and the 4-D Cockpit Situational Display (4D-CSD). MUSIM is a suite of programs that allows for simulation of a UAS ground control station (GCS) that was developed jointly by NASA and the Army (Fern & Shively, 2011). MACS is a medium-fidelity ATC/Pilot simulation software developed by NASA Ames' Airspace Operations Lab (Prevot, 2002), and the 4D-CSD is an advanced cockpit display developed by NASA Ames' Flight Deck Display Laboratory (Granada, Dao, Wong, Johnson, & Battiste, 2005). MACS was used to simulate the air traffic environment including the ATCo radar screen of a low-altitude sector in LA center airspace, where the UAS was located. No other traffic was present in the sector. MUSIM was used by the pilots to control the UAS during the simulation. The 4D-CSD was mainly used a supplemental navigation display. Voice communication between controllers and pilots was provided by a voice server station via push-to-talk headsets.

Design

This simulation was designed to exercise our ability to capture the MR components using MUSIM as a GCS testbed. We manipulated the clearances issued and measured the MR components.

Thus, our Independent Variable was clearance type. We issued 15 clearances, including two variants of the first 6 clearance types, and three variants of the final, frequency change clearance listed below:

1. Crossing Restriction: PD-1 cross [insert waypoint name] at [1,000ft] above/below current altitude
2. Direct To: PD-1 turn left/right [insert heading] direct: [insert waypoint name], then resume own navigation
3. Route Amendment- Altitude: PD-1 climb/descend and maintain [1,000ft above/below current altitude]
4. Route Amendment- Heading: PD-1 turn right/right, fly heading 090/270
5. Route Amendment- Altitude + Traffic Alert: PD-1 climb/descend and maintain [1,000ft above/below current altitude], issue nearest proximal traffic
6. Traffic Alert with Immediate Turn: PD-1, traffic [nearest proximal traffic; o'clock position and altitude]; turn left/right immediately, fly heading: [insert heading to left/right of current location]
7. Frequency change: PD-1 contact center/approach/tower [insert frequency]

The dependent variables were the time associated with the 3 MR components: MR1- Communication Lag: Time between when the ATCo completed issuing the command to when the pilot began verbal readback; MR 2- Execution Lag: Time between when the ATCo ended issuing the command to when the pilot began to execute the command; MR 4- Display Lag: Time between when the aircraft began to maneuver (which was measured in this simulation as when the pilot completed the execution of the command because the version of MUSIM we used had instantaneous maneuver of the aircraft with the pilot execution of the command) to when the information of the change in the aircraft's state was first available on the ATCo's scope. MR 3- Aircraft Lag: Time between when the pilot completed the execution of the command to when the aircraft began its maneuver was not captured. As noted earlier, the version of MUSIM we used had instantaneous maneuver of the aircraft with the pilot execution of the command.

In addition, we measured pilot workload and ATCo acceptability of the promptness of pilots' responses. Both of these were subjective measures captured at the end of each trial using a Likert-like scale.

Procedure

All pilots received MUSIM training as part of another simulation (unrelated to the MR project). When they arrived for the present simulation, the pilots were asked to complete a demographics questionnaire. Then, they were given a short introduction to the purpose of the study and its procedures. The pilots were told that they will be asked to execute a series of clearances issued by an ATCo, and that they were to respond to the clearance. All pilots were given a few minutes to re-familiarize themselves with MUSIM. After executing each clearance, the pilot was asked to rate subjective workload on a scale from 1 (Very Low Workload) to 7 (Very High Workload).

One of our two ATCos read the clearance to the pilot participants. We did not control for ATCo, as the ATCo for any particular day depended on his availability to participate in the study. The order in which the clearance was read was partially counterbalanced for clearance type across participants. The ATCo was also asked to determine when the UAS completed executing the clearance to move on to the next trial. Before issuing the next clearance, the ATCo was asked to rate the acceptability (in terms of promptness) of pilot's execution of his last clearance on a scale from 1 (Not Acceptable at All) to 7 (Highly Acceptable).

Each of the 15 total clearances was issued once in a block of trials that took approximately 10 minutes. Each participant was run through two blocks of trials. The total time each participant took to run in the study was approximately 30 minutes, including set-up time, and time to fill out the demographic questionnaire.

Analysis of Data

The mean time (i.e., averaged across the two blocks of trials) for each of the three MR components was obtained for each participant. In several cases, there were negative times for the MR components. The negative times were due to pilots carrying out the MR components in parallel. Because we wanted to get a measure of the pure components, we "zeroed" all negative values when computing the means below. Descriptive analyses were performed for each the MR components measured.

We also used paired t-tests to determine if the time for each MR component, for each clearance type, differed from the first to second block of trials to determine whether practice effects were evident.

Finally, we used correlation analyses to determine whether the time for the MR components, by clearance type, was correlated with the pilot workload rating and/or ATCo acceptability rating.

RESULTS

Descriptive Analyses

We provide the overall means and standard deviations for the MR components as a function of the clearance issued separately for each MR component in Table 1.

Practice Effects

Comparison of the response times for each MR component as a function of clearance type only showed two significant effects. The communication lag (MR 1) component for the crossing restriction clearance was faster during the second block ($M = 4.25$ s) than during the first block ($M = 11.11$ s), $t(13) = 3.70$, $p = .003$. In addition, for the traffic alert + immediate turn clearance, the display lag (MR 4) was also faster during the second block ($M = 2.29$ s) than during the first block ($M = 3.04$ s), $t(13), = 2.27$, $p = .041$. No other effects were significant, indicating that practice had very little effect on the data.

Correlational Analyses

We performed correlational analyses to determine whether the MR components for each clearance were correlated with either Pilot workload ratings or ATCo acceptability ratings.

For workload ratings, none of the MR components for any of the clearance type was significantly correlated with pilot workload. For ATC acceptability ratings, only a handful of MR components by clearance type were significantly correlated with ATC acceptability.

For Direct to clearances, the execution lag (MR 2) was negatively correlated with the ATC acceptability rating, $r(12) = -.61$, $p = .02$. For the Route Amendment – Altitude + Traffic clearance, the communication lag (MR 1) was positively correlated with the ATC acceptability rating, $r(12) = .58$, $p = .03$, but the execution lag (MR 2) was negatively correlated with the ATC acceptability rating, $r(12) = -.83$, $p > .001$. Finally, for the Route amendment – Altitude clearance, the execution lag (MR 2) was negatively correlated with the ATC acceptability rating, $r(12) = -.661$, $p = .01$.

Table 1: Means and Standard Deviations (in Parentheses) for each MR component as a function of Clearance Type. Pilot workload and ATC acceptability ratings for the corresponding clearance type are also provided.

	Clearance Type						
Measures	**Crossing Restriction**	**Direct To**	**Frequency**	**Route Amend-Altitude+ Traffic**	**Route Amend-Heading**	**Route Amend- Altitude**	**Traffic Alert + Immediate Turn**
MR1 Time (in seconds)	2.75 (.70)	2.64 (.82)	2.24 (.62)	2.41 (.57)	2.77 (2.0)	2.13 (.34)	2.76 (1.18)
MR2 Time (in seconds)	7.63 (5.66)	7.32 (7.14)	n/a	1.88 (2.17)	4.77 (3.11)	2.63 (1.91)	1.70 (.93)
MR3 Time	Not captured because event occurs instantaneously in MUSIM						
MR4 Time (in seconds)	4.38 (2.75)	2.84 (1.36)	n/a	4.00 (1.99)	3.07 (1.15)	4.11 (1.43)	2.61 (1.70)
Pilot Workload Rating (1= Very low; 7 = Very high)	2.25 (1.04)	2.2 (0.88)	1.32 (.44)	1.61 (.67)	1.63 (.71)	1.45 (.56)	1.79 (.75)
ATC Acceptability Rating (1= Not Acceptable; 7 = Highly Acceptable)	6.10 (.51)	6.15 (.71)	6.87 (.35)	6.55 (.51)	6.39 (.49)	6.38 (.56)	6.51 (.59)

DISCUSSION

This simulation showed that the MR components could be extracted successfully from the MUSIM GCS and MACS ATCo configuration, making MUSIM a feasible testbed for studying UAS operations in future studies. The average communication lag (MR 1 component) was approximately 2.5 seconds. Although the communication lag did differ somewhat across clearance types, the differences were small. This finding indicates that pilots promptly acknowledge ATCo clearances regardless of the exact clearance being issued to them. However, because the UAS pilots were not doing any other tasks, it may be the case that the pilots will show more variability in the operational environment when they have to prioritize the different tasks they are being asked to perform.

The execution lag (MR 2 component) varied widely between clearance types as well as within a clearance type, as indicated by the fact that the standard deviation is oftentimes as large as the mean values. The wide variation in time between clearances can be attributed to the fact that pilots are able to start executing certain ATCo commands before the ATCo clearance is completely issued. We did observe negative execution lags in the data for the MR 2 component, which supports the notion that pilots do not wait for the entire clearance to be read before they start executing their commands. As such, the MR components can begin before the MR 1 component.

The display lag (MR 4 component) showed some variance between clearance types, but the differences were much smaller than that for MR 2. MR 4 is influenced by the update rate on the ATCo's scope, which was set to 1 second in the current simulation to reflect ADS-B update rates. However, because the component was extracted using post-simulation video of the ATC scope, the actual update rate could have been as much as 2 seconds (the 1 second update rate for the scope and an additional 1 second screen recording rate of the software). This difference in time may not be as important to the ATCo because once the pilot acknowledges the clearance (MR 1), then the ATCo knows that the pilot received the clearance instruction and simply needs to check the aircraft state to determine if the pilot is executing the clearance correctly. In certain environments, such as en route, ATCo can move on to other tasks and check back about the status of the aircraft state when convenient, rather than continuously monitoring the aircraft state. This ability to check back later makes the promptness of the display lag less important. This is especially the case when the update rate of the radar sweep is long. In other environments and situations, such as closer to the airport and during emergencies, the ATCo will need to check the aircraft status more often and thus accurate lag times and measurement of these times is critical for future studies.

Although the participants were given each clearance twice, once in block 1 and again in block 2, there was little evidence for practice effects. The lack of a practice effect is likely due to the pilots already being familiar with the MUSIM interface through their participation in prior simulations using MUSIM. In future studies, researchers need to make sure that the pilots are highly trained before the experimental runs to rule out practice effects.

The MR components did not correlate with pilot workload. However, the lack of significant correlations was probably a result of the pilot workload ratings being relatively low in most situations. More interesting was the fact that execution lag (MR 3 component) was shown to be negatively correlated with ATC acceptability ratings for a few of the clearances. The negative direction of the correlation indicates that shorter execution times are associated with higher ATCo acceptability ratings. There was only one positive correlation for communication lag (MR 1 component) in which the longer lag was associated with higher ATCo acceptability. There was no obvious reason for the positive correlation. However, because the specific clearance had a traffic alert, it could be the case that the controller was expecting the pilot to locate the traffic before responding. This explanation, though, is only speculative.

The goal of the study was to develop the methodology to capture measured response components of UAS pilots using MUSIM as a GCS testbed. As such, the simulation environment used in the study was simple. There was also no other traffic in the sector with the UAS and the UAS pilot was not doing any other tasks associated with typical UAS operations during this simulation. The pilot response times may be longer under conditions of higher workload, which may affect ATC acceptability ratings. In addition, the data presented in this study reflects a small sample of pilots, who are professional pilots but are not actual UAS pilots. As such, the numerical values may not reflect those obtained using actual UAS pilots.

Future research of measured response is needed to support development of standards, regulations, and policy regarding safe integration of UAS into the NAS. This study was an initial and limited evaluation, providing the framework for future research that should include additional UAS make/models, classes of airspace, traffic densities, mixture of UAS and manned aircraft, and other variables. This will provide a more comprehensive and in-depth understanding of overall MR, the contribution of each MR component, and potential UAS design modifications needed to reduce MR to response times observed with manned aircraft. This will allow UAS to respond to ATC clearances in a timely manner and adhere to the same minimum separation standards as manned aircraft.

REFERENCES

Blickensderfer, B., Buker, T. J., Luxion, S. P., Lyall, B., Neville, K., & Williams, K. W. (2012). The design of the UAS ground control station: Challenges and solutions for ensuring safe flight in civilian skies. In *Proceedings of the Human Factors and Ergonomics Society 56th Annual Meeting* (pp.51-55). Santa Monica, CA: Human Factors and Ergonomics Society.

Fern, L., & Shively, J. (2011). Designing airspace displays to support rapid immersion for UAS handoffs. In *Proceedings of the Human Factors and Ergonomics Society 55th Annual Meeting* (pp. 81–85). Santa Monica, CA: Human Factors and Ergonomics Society.

Gawron, V. J. (1998). Human factors issues in the development, evaluation and operations of uninhabited air vehicles. In *Proceedings of the Association for Unmanned Vehicle Systems International* (pp. 431-438), Huntsville, AL.

Granada, S., Dao, A. Q., Wong, D., Johnson, W. W., & Battiste, V. (2005). Development and integration of a human-centered volumetric cockpit display for distributed air-ground operations. In *Proceedings of the 12th International Symposium on Aviation Psychology*, Dayton, OH.

Merlin, P. W. (2009). *Ikhana unmanned aircraft system Western states fire missions*. Washington, DC: National Aeronautics and Space Administration.

Mouloua, M., Gilson, R., Kring, J., & Hancock, P. (2001). Workload, situational awareness, and teaming issues for UAV/UCAV operations. In *Proceedings of the Human Factors and Ergonomics Society 45th Annual Meeting* (pp. 162-165). Santa Monica, CA: Human Factors and Ergonomics Society.

Prevot, T. (2002). Exploring the many perspectives of distributed air traffic management: The Multi Aircraft Control System: MACS. *International Conference on Human–Computer Interaction in Aeronautics, HCI–Aero 2002*, 23–25.