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Effect of Control Latency on Unmanned Aircraft Systems During Critical Phases of Flight

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EFFECT OF CONTROL LATENCY ON UNMANNED AIRCRAFT SYSTEMS DURING CRITICAL PHASES OF FLIGHT

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Unmanned Aircraft Systems (UAS) are controlled remotely via terrestrial or satellite-based radio link rather than by a pilot in the cockpit. The remote nature of the transmission results in latencies (time between pilot input and feedback indicating aircraft response) that are typically longer than those in manned aircraft. Researchers from the FAA Human Factors Branch conducted a simulation to investigate the effect of control latencies during takeoff and landing scenarios in UAS with low levels of automation. We evaluated one of four latencies (180, 494, 750, 1026 ms) in each test scenario. Half of the scenarios included crosswinds. Data obtained from 11 UAS pilots indicated that as latency increased aircraft performance and pilot ratings of aircraft handling were negatively affected (e.g., more deviations from pattern). Overall, control latencies above 494 ms adversely affected pilot and aircraft performance relative to baseline.

Unmanned aircraft systems (UAS) are increasingly identified for use in diverse activities such as aerial photography, package delivery, surveillance, and search and rescue. The Association for Unmanned Vehicle Systems International (Jenkins & Vasigh, 2013) predicted that the UAS industry will generate $10 billion of annual revenue once UAS are integrated into the National Airspace System (NAS). To integrate UAS into the NAS, the FAA needs to determine the characteristics that define acceptable UAS performance to ensure that the NAS maintains the highest levels of safety and efficiency. UAS are piloted remotely via terrestrial or satellite-based radio link that result in control latencies that are typically longer than those in manned aircraft. UAS control latencies range from hundreds of milliseconds to several seconds (Walsh, 2009), whereas manned aircraft control latencies are typically less than 150 milliseconds (e.g., Berry, 1985). Control latencies have a substantial impact on precision motor control tasks (e.g., Chen, Haas, & Barnes, 2007) and this effect is difficult or impossible to overcome (Taylor & Zingale, 2014). Hence, it is essential for the FAA to know the specific impact that latencies of various magnitudes may have on UAS operations.

Methods

Eleven Air Force pilots, with experience in UAS launch and recovery (takeoff and landing) operations, participated in this simulation at the FAA William J. Hughes Technical Center's NextGen Integration and Evaluation Capability (NIEC) Laboratory. The pilots used a UAS simulator with a stick and rudder control system to complete short (7 minute) takeoff and landing scenarios under four different control latencies (180, 494, 750, 1026 ms). The latencies included the "TT95" values (time before which 95% of transactions are completed) reported by Walsh (2009) for line-of-sight (494 ms) and beyond-line-of-sight (1026 ms) operations. We included a baseline latency of 180 ms to correspond to the latency of a comparable aircraft with no wireless control link. Half of the scenarios included crosswinds. The simulator heads-up displays showed an out-the-window view from the UAS and, separately, showed an overview sectional map that depicted the traffic pattern overlays and a restricted operating zone (ROZ) outside the patterns. The simulator recorded pilot control inputs and aircraft performance outputs, positions, and attitudes. An FAA pilot who was part of the research team acted as the sensor operator (SO) to provide call-outs as requested by the pilot (e.g., stating current altitude) and to record the time at which a pilot indicated a need to execute a go-around.

Experimental Design

We had three primary independent variables: latency, phase of flight (takeoff vs. landing), and presence or absence of crosswinds (0 or 14 knots). We ran half of the test scenarios with left closed turns and the other half with right closed turns. We randomized test orders for each participant and counterbalanced test orders across participants.

Procedure

Before each scenario, the researchers informed the pilot of the control latency (180, 494, 750, or 1026 ms), whether or not crosswinds would be present, and the traffic pattern direction. For all scenarios, pilots were instructed to stay within +/- 100 feet of the target altitude of 1,000 ft (+/- 10 knots of the target velocity of 105 knots) and within +/- 5 degrees heading as depicted by the pattern overlay. For takeoff scenarios, pilots were instructed to take off from the assigned runway, to climb to the traffic pattern altitude, and to make the appropriate turns. For landing scenarios, pilots started in the air at the mid-way point of the downwind leg and were instructed to complete their approach along the indicated pattern and come to a full stop on the runway. Pilots were told to *always land the aircraft* unless otherwise advised by their SO. In the event they would have executed a go-around, the pilots were instructed to alert the SO, who recorded this information. After each scenario, the pilots completed questionnaires that included the Cooper-Harper (CH) Handling Qualities Ratings Scale (Cooper & Harper, 1969) to provide an assessment of aircraft performance. Ratings on the CH scale range from 1 (*satisfactory*) to 10 (*uncontrollable*).

Data Analysis

We analyzed data on aircraft and pilot performance, including location of UAS during flight relative to pattern and runway centerline; variability in pilot command entries; deviation between target and actual UAS altitude; frequency of go-around requests; aircraft force at touchdown; and questionnaire ratings. We analyzed data from the takeoff and landing scenarios separately using Bayesian hierarchical linear modeling. We chose this framework because our design was unbalanced and to model outliers using robust estimation techniques (see Kruschke, 2010). Our predictor variables were latency, presence of crosswinds, and latency/crosswind interaction. To obtain credible values for our predictors, we estimated the “posterior” distribution of their regression coefficients via Markov Chain Monte Carlo. We report the “high-density interval” (HDI) from the posterior, or the range of most credible coefficients. Formally, the HDI is the interval corresponding to 95% of the posterior probability mass. Bayesian analysis does not entail the computation of *p*-values, but one may consider an effect “significant” if the HDI does not include 0. To provide maximum information pertaining to latency, we report the predicted impact of latency for conditions with crosswinds and without crosswinds separately. We do not provide HDIs for the effects of crosswinds because winds were not the focus of the report.

Results

We measured aircraft deviation from the flight path and runway centerline to evaluate performance while in the pattern and over the runway, respectively. Figure 1 presents the mean aircraft deviations from the pattern overlay for the takeoff scenarios (left) and the landing scenarios (right).

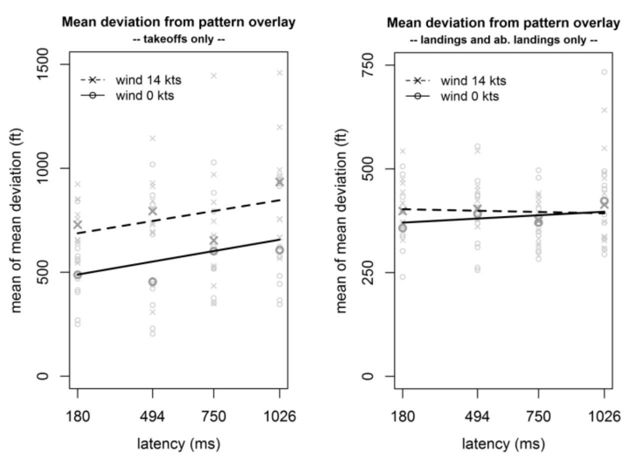

Figure 1. Summary of mean deviations from the pattern during takeoffs (left) and landings (right). Light grey points indicate means for each participant. Dark grey points indicate medians across participants. Black lines indicate the average regression fit from Bayesian analysis.

For takeoffs, the effect of latency was significant with and without crosswinds. Credible values for the latency effect in the presence of crosswinds were between 0.0321 and 0.3425 (95% HDI): an increase between 32.1 and 342.5 feet per second of added latency. Credible values for the latency effect in the absence of crosswinds were between 0.0423 and 0.3501 (95% HDI): an increase between 42.3 and 350.1 feet per second of added latency. For landings, the effect of latency was not significant for either crosswind condition.

We evaluated pilot adherence to the target altitude of 1,000 ft (+/-100 ft) while in the pattern. Figure 2 presents the aircraft deviations from the target altitude for takeoffs (left) and landings (right). For takeoffs, only the effect of latency in the presence of crosswinds was significant, with credible values between 0.0015 and 0.0428 (95% HDI): an increase between 1.5 and 42.8 feet per second of added latency. For landings, the effect of latency was not significant for either crosswind condition.

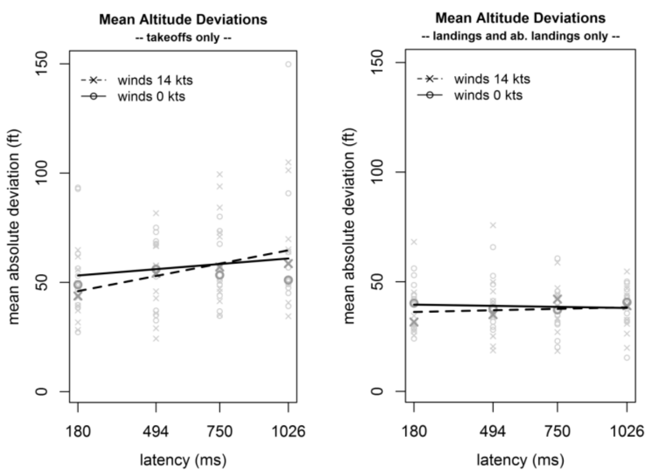

Figure 2. Summary of mean aircraft altitude deviations during takeoffs (left) and landings (right). Light grey points indicate means for each participant. Dark grey points indicate medians across participants. Black lines indicate the average regression fit from Bayesian analysis.

We measured the number of times the participants indicated they would have executed a go-around for each latency and crosswind condition. Figure 3 presents the mean proportion of indicated go-arounds for each latency condition. In this analysis, we used a logistic link function to model the raw binary responses. Only the effect of latency in the absence of crosswinds was significant, with credible values between 0.0003 and 0.0032 (95% HDI): an increase of approximately 17% more go-arounds from 0 to 1 seconds of latency.

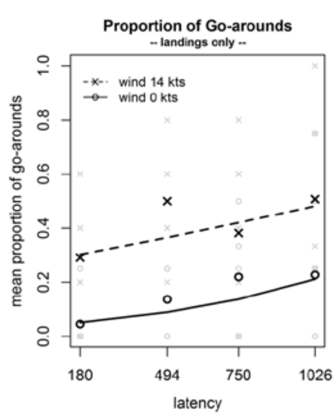

Figure 3. Summary of mean proportion of indicated go-arounds. Light grey points indicate means for each participant. Black points indicate means across participants. Black lines indicate the average regression fit from Bayesian analysis.

For landing scenarios, we also evaluated force of the unmanned aircraft (UA) at touchdown by analyzing the weight applied to the UA landing gear. We computed the maximum weight across the first five seconds after the initial point of touchdown. An example of a rough landing showed a weight of ~7,000 lbs applied at the initial point of touchdown, then another weight of ~15,000 lbs shortly after—whereas, an example of a smooth landing showed a weight of ~2,500 lbs applied at the initial point of touchdown. On average, maximum force at touchdown values for each pilot ranged, approximately, from 5,000 to 15,000 lbs. Only the effect of latency in the absence of crosswinds was significant, with credible values between 0.4510 and 5.6004 (95% HDI): an increase between 451.0 and 5,600.4 lbs per second of added latency.

For each pilot, we calculated the mean and maximum pilot CH rating for each combination of latency and crosswind conditions. We considered the maxima in addition to the means because allowable control latencies for UAS must ensure acceptable performance across a range of performance levels, not merely the average. The effect of latency, with and without crosswinds, was significant for both the mean and maximum ratings (see Figure 4). For mean ratings, credible values for the latency effect in the presence of crosswinds were between 0.0028 and 0.0052 (95% HDI): an increase in 2.8 to 5.2 points on the CH scale per second of added latency. Credible values for the latency effect in the absence of crosswinds were between 0.0022 and 0.0042 (95% HDI): an increase in 2.2 to 4.2 points on the CH scale per second of added latency. Maximum ratings were 1-2 points higher than mean ratings. For maximum ratings, credible values for the latency effect in the presence of crosswinds were between 0.0029 and 0.0050 (95% HDI): an increase in 2.9 to 5.0 points on the CH scale per second of added latency. Credible values for the latency effect in the absence of crosswinds were between 0.0027 and 0.0049 (95% HDI): an increase in 2.7 to 4.9 points on the CH scale per second of added latency. Critically, latencies in excess of 494 ms in conditions with 14 knot crosswinds resulted in maximum ratings in the "inadequate" handling qualities range.

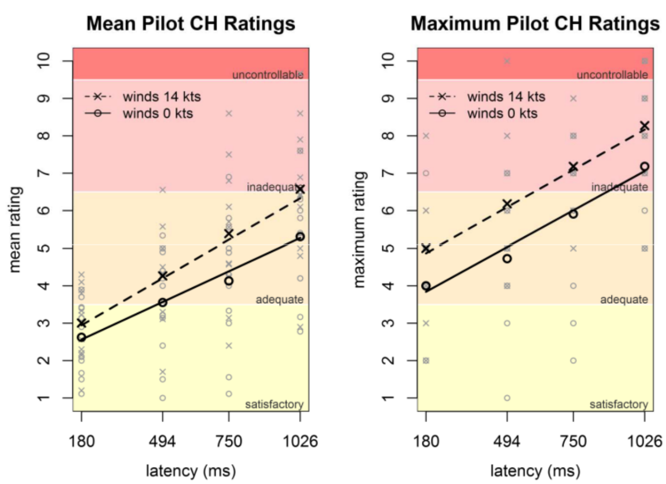

Figure 4. Summary of mean and maximum Cooper-Harper ratings. Light grey points indicate individual means for each participant. Black points indicate means across participants. Black lines indicate the average regression fit from Bayesian analysis.

We also considered objective measures of control difficulty by evaluating two measures of pilot command input variability for yaw, pitch, and roll per scenario: (1) the standard deviations of the control surface deflections to capture the frequency and magnitude of command use and (2) the maximum input deflections to capture the most extreme inputs. The results from these analyses revealed that the participants used significantly more variable and extreme yaw inputs when aircraft were over the runway in conditions with higher control latencies (see Figure 5). The effect of latency on standard deviations of control surface deflections was significant with and without crosswinds. Credible values for the latency effect in the presence of crosswinds were between 0.00007 and 0.0025 (95% HDI): an increase between 0.07 and 2.5 degrees per second of added latency. Credible values for the latency effect in the absence of crosswinds were between 0.0006 and 0.0030 (95% HDI): an increase between 0.6 and 3.0 degrees per second of added latency. Likewise, the effect of latency on maximum input deflections was significant with and without crosswinds. Maximum yaw inputs indicated that the credible values for the latency effect in the presence of crosswinds were between 0.00005 and 0.0050 (95% HDI): an increase between 0.05 and 5.0 degrees per second of added latency. Credible values for the latency effect in the absence of crosswinds were between 0.0015 and 0.0076 (95% HDI): an increase between 1.5 and 7.6 degrees per second of added latency.

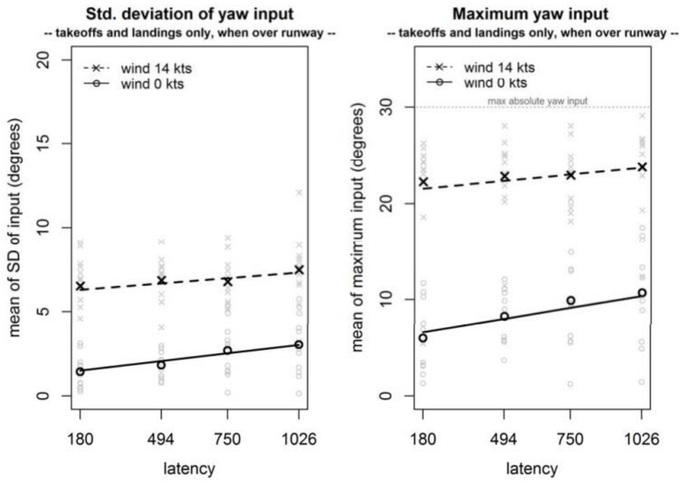

Figure 5. Summary of yaw input standard deviations (left) and maximum inputs (right) for aircraft over the runway in takeoff and landing conditions. Light grey points indicate means for each participant. Black points indicate means across participants. Black lines indicate the average regression fit from Bayesian analysis.

Discussion

Our simulation found that longer control latencies had an adverse effect on aircraft and pilot performance during takeoffs and landings in UAS with low levels of automation. These findings are consistent with prior research in aircraft simulators and in generic tracking tasks which show that latency impacts performance and subjective ratings of aircraft handling qualities. To our knowledge, however, this is the first study to directly measure the impact of latency on specific variables (e.g., go-around propensity and deviation from predetermined flight paths, which are directly relevant to UAS integration into the NAS).

We found that pilots indicated a need to execute more go-arounds with higher latencies. Nearly as many go-arounds were requested with 494 ms of latency as with 750 ms and 1026 ms. Force at touchdown as well as the number and extent of yaw inputs increased significantly as a function of latency. CH ratings increased notably with higher latencies, and maximum pilot CH ratings were in the “inadequate” range of the scale in conditions with latencies exceeding 494 ms when crosswinds were present. We also found that aircraft deviated more from the pattern and from the designated altitude with higher latencies during takeoffs. Interestingly, deviation from the runway centerline on landing was not significantly impacted by latency. We speculate that takeoffs in our simulation may have required more effort because the patterns called for the pilots to execute two turns almost immediately after takeoff. Thus, pilots may have been rushed to set their desired levels of power and trim commands. In contrast, pilots had more time during landing to prepare for final descent because the downwind leg allowed a long approach. Indeed, we designed our landing scenarios to incorporate a long approach based on feedback from UAS subject matter experts.

Acknowledgments

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