ASSESSMENT OF UNMANNED AIRCRAFT PLATFORM PERFORMANCE USING MODELING AND SIMULATION

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ABSTRACT

Unmanned aircraft systems (UAS) can provide significant enhancement to capability, when used in a manner best aligning inherent design characteristics to requirements of a given application. However, wide variability in designs, configurations, and operational attributes requires the performance of thorough investigation to appropriately identify suitable platforms. Failure to perform sufficient examination can lead to expensive cost overruns, diminished capability, and degraded safety. Assessing the capabilities and performance associated with categorized UAS platforms through experimentation and analysis can produce valuable insight regarding propriety for application. The use of modeling and simulation (M&S) provides the means to identify limitations, benefits, and considerations necessary to aptly employ UAS. Understanding how to best select, configure, and apply this rapidly advancing technology is anticipated to support increased innovation, safety, efficiency, and effectiveness; elements essential to achieving successful integration into the National Airspace System (NAS) for use across government, industry, and academia. This paper contains a description of continued work from an experimental research project featuring use of M&S to identify, observe, and investigate critical factors of UAS platform application in an efficient and expedient manner. Operational design attributes (i.e., published and derived metrics) of 282 commercially-off-the-shelf (COTS) platform configurations were identified, classified, and analyzed to create category representative UAS performance models. These models were employed in 30 experimental trials and subsequent statistical analysis. The results led to the development of a theory of operation, selection requirements for use of UAS in aircraft rescue and fire fighting (ARFF), and an expanded series of UAS category performance models. Future anticipated research, including improvement of performance models, expanded simulation trials, and further refinements will also be discussed.

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INTRODUCTION

The use of unmanned aircraft systems (UAS), by both public agencies and private (civil) operators, continues to steadily increase based on technological advances, an evolving regulatory framework featuring improved governmental accommodation, public education and outreach, and availability of personnel with related subject matter expertise (Federal Aviation Administration [FAA], 2015a; 2015b; John A. Volpe National Transportation Systems Center, 2013; Terwilliger, 2015; Terwilliger et al., 2015a). UAS can significantly enhance the capabilities of a user, such as a government agency or business, when used in a manner best aligning inherent design characteristics to requirements of a given application. However, wide variability in designs, configurations, operational attributes, environmental factors, and functional requirements require thorough investigation and consideration to address and appropriately identify suitable platforms. Failure to perform sufficient investigative examination can lead to tasking disparity, expensive cost overruns, diminished capability, and degraded safety. Assessing the capabilities and performance associated with categorized UAS platforms through experimentation and analysis can provide valuable insight regarding applicability and appropriateness for considered applications. Availability and use of modeling and simulation (M&S) techniques, tools, and data supports the identification of critical considerations necessary to employ UAS technology effectively. Understanding how to best select, configure, and apply this rapidly advancing technology is anticipated to support increased innovation, safety, efficiency, and effectiveness; elements essential to achieving successful integration into the National Airspace System (NAS) for use across government, industry, and academia (Terwilliger, Vincenzi, & Ison, 2015).

This paper contains the details of an ongoing experimental research project featuring use of M&S to identify, observe, and investigate critical factors of UAS platform configuration application in an efficient and expedient manner. Operational design attributes (i.e., published and derived metrics) of 282 commercially-off-the-shelf (COTS) UAS platform configurations were identified, classified, and analyzed to create a series of category representative performance models. These models were incorporated into 30 experimental trials (i.e., simulated scenarios) to observe effects and generate data for subsequent statistical analysis. The results of an initial experiment led to development of a theory of operation, recommended selection requirements (criteria), and identification of need for further expansion of category performance models supporting a use case of UAS aircraft rescue and fire fighting (ARFF) response (Terwilliger et al., 2015a). The continued goal of this project is to assess mission parameters (needs) and match with appropriate equipment, while taking into account prior recommendations and factors that could affect operational performance and safety. Implications for addressing challenges are discussed as they relate toward optimizing benefits, effectiveness, safety, and specified application support. Suggested recommendations, including future research, improvement of performance models, expanded simulation trials, and further refinements are also discussed. Observations and findings of this investigation indicate the effectiveness of simulated UAS performance modeling, and application analysis, in addition to identification of specific UAS platform types to support the subject application (ARFF response operations).

PURPOSE

The use of UAS to support ARFF response in times of emergencies is a relatively new and controversial concept because the area in which these systems need to operate (i.e., on or near airport property and within controlled airspace) is restricted and highly regulated by the FAA (2015a). Aircraft accidents on takeoff and landing, while uncommon, result in significant potential for death, injury, and damage; requiring first responders to be prepared to address a diverse range of dynamic situations (Airbus, 2013; McCoy, 2014). The ability to acquire and communicate advance knowledge to first response personnel when unexpected disasters and hazardous situations occur is imperative and invaluable as their ability to react to an emergency is dependent on the "quality, accuracy, timeliness, and usability of information" (Terwilliger et al., 2015b, p. 246). Accurate information, obtained immediately following the event and before personnel are on site, can result in safer execution of emergency procedures and responses, more efficient positioning and use of resources, and more effective response from personnel arriving on the scene (Terwilliger et al., 2015a). Disaster situations are typically emotionally charged, confusing, and chaotic; the more data made available to first responders, in an intuitive and comprehensive manner before they arrive on scene, the more effective their response will be (Terwilliger et al., 2015b). With aviation accidents, such as the Asiana Airlines Flight 214 crash at San Francisco International Airport (McCoy, 2014), the ability to arrive early on scene to assess and obtain situational awareness (i.e., state of accident), distribute information, and position ARFF assets in an expedited and efficient manner may reduce the potential for accidental passenger death and injury (Terwilliger et al., 2015b). Such enhancement is anticipated to translate into improved response times, diminished risk for both responders and victims, and reduced loss of life.

METHOD and EXPERIMENTATION

Obtaining improved understanding of UAS platform configuration type (categories) performance, in relation to specific use, provides the insight necessary to apply the technology in a safe, efficient, effective, and appropriate manner (Stansbury et al., 2015; Terwilliger et al., 2015a). Examining the employment of application analysis, in a useful and necessary context, required adaptation and configuration of the assessment specific to UAS-ARFF response. Specifically, to measure potential effectiveness of UAS response, compared to conventional ARFF response, to gain further knowledge regarding the possibility of enhancing current response capability. In support of this objective, a series of quantitative experimental studies were performed starting with an investigation of the effectiveness of group 1-3 UAS platform configurations (fixed-wing and vertical takeoff and landing [VTOL]), immediately followed by development of six new categories (Stansbury et al., 2015). The classification criteria for the new categories were based on findings and recommendations of the initial study, including identification of a set of recommended requirements (Terwilliger et al., 2015a), which resulted in designation and creation of the optimal category (Stansbury et al., 2015).

The focus of this study was placed on examining potential effectiveness of the new categories for UAS-ARFF response to further identify viable candidate platforms and desirable attributes. This was achieved by determining calculated response rate (dependent variable or effect) of several defined UAS categories (independent variable or treatment; e.g., UAS platform configuration types) to 30 simulated aviation accidents within a five-mile radius of an airport (experimental trials). A series of extraneous control variables (environmental and typical accident conditions) were established after investigation of past fatal accidents, nationwide weather conditions, and features of a subject airport. The individual trials were used to perform a series of experiments in the application analysis framework and calculate anticipated response rate of each treatment using a prescribed theory of operation (e.g., launch, forward flight, orbit around accident, return to base, and recovery). Each experimental treatment represents an individual performance model, while the control treatment was represented using a calculated conventional ARFF response.

Research Plan

A multiple-phase research plan was created for this continuous project, which included the following stages:

1. Develop necessary research infrastructure and elements
    a. Category representative UAS performance models; data capture, calculation, and development
    b. Theory of operation; define for specific application
    c. Experimental scenarios; data capture, calculation, assignment, and development process
    d. Application analysis framework; development, application specific customization, and verification
2. Perform experimentation
3. Perform analysis
4. Identify findings and implications
5. Update models, framework, and theory of operation; continuing to update as relevant information or resources become available
6. Perform longitudinal research; high-level pursuits and proposed activities identified, anticipate in-depth investigation and pursuance as relevant information or resources become available

Category Representative UAS Performance Models

A series of UAS statistical analysis models, termed attribute performance models (APMs), were created to calculate and exhibit critical performance capabilities of unique UAS categories. Initially, 150 UAS platform configurations were examined, documented, and categorized using Department of Defense (DOD) UAS classification criteria into group 1-3 (US Army UAS Center of Excellence [COE], 2010, p. 12; Terwilliger et al., 2015a). These categories were further subdivided into fixed-wing and VTOL platforms for each group (group 1 fixed-wing, group 1 VTOL, group 2 fixed-wing, group 2 VTOL, group 3 fixed-wing, and group 3 VTOL). As the research proceeded, details for an additional 132 platform configurations were acquired, increasing the total number of UAS examined and available for analysis to 282 (*N*=282; Stansbury et al., 2015; Terwilliger et al., 2015a). Group 1 fixed-wing (*n*=56) and VTOL (*n*=45) represent small UAS (sUAS) with a maximum gross weight of 20 pounds or less, normal operating altitude of less than 1200 feet above ground level (AGL), and an airspeed capability less than 100 knots (kts; US Army UAS COE, 2010). Group 2 fixed-wing (*n*=45) and VTOL (*n*=45) represent sUAS with a maximum gross weight between 20 to 55 pounds, normal operating altitude of less than 3500 feet AGL, and an airspeed capability less than 250 knots (kts; US Army UAS COE, 2010). Group 3 fixed-wing (*n*=46) and VTOL (*n*=45) represent UAS with a maximum gross weight between 55 to 1320 pounds and a normal operating altitude of less than 18000 feet mean sea level (MSL; US Army UAS COE, 2010).

The APMs were developed by calculating and assigning representative attributes (mean values from categories) using baseline data from the 282 UAS platform configurations. These attributes included cruise speed (kts), maximum speed (kts), operational altitude (feet AGL), maximum altitude (feet above MSL), endurance (minutes), one-way range at cruise speed (statute miles [SM]), round-trip range at cruise speed (SM), payload capacity (lbs), empty weight (lbs), maximum gross weight (lbs; i.e., maximum takeoff weight [MTOW]), propulsion type (internal combustion or electric), wind limit (kts), and system cost (USD). Four of the attributes are critical for performance of calculations in the application analysis; cruise speed, maximum speed, endurance, and one-way range.

Completion of the initial UAS-ARFF application experiment resulted in the development of a series of documented observations and recommended platform requirements, which led to creation of six additional categories used in this experiment (Terwilliger et al., 2015a). Common UAS attribute and classification nomenclature, as well as unique characteristics, were used to define these new categories; tube-launched platforms, optimal platforms, fixed-wing sUAS, VTOL sUAS, electric sUAS, and internal combustion sUAS. Tube-launched platforms (*n*=12) represent UAS with an air vehicle element capable of being propelled from a portable enclosure (e.g., mortar tube), which may facilitate expedited deployment. The optimal platform category (*n*=14) represent those UAS with attributes meeting the recommended requirements from the initial study (e.g., electric propulsion, cruise speed of at least 25kts, endurance of at least 25 minutes, payload capacity of at least one pound, and wind capable of at least 15kts; Terwilliger, et al., 2015a). The four remaining categories represent sUAS platforms with a MTOW up to 55 pounds, normal operating altitude less than 500 feet AGL, airspeed restricted to 100 knots, and exhibiting the title feature of the respective category (fixed-wing [*n*=101], VTOL [*n*=90], electric [*n*=148], or internal combustion sUAS [*n*=43]). The four critical values associated with each new APM created for this study are depicted in Table 1.

Table 1. Critical UAS APM values

UAS APM Type	Cruise Speed (kts)	Maximum Speed (kts)	Endurance (minutes)	Range (SM)
Tube-launched Platforms	44.38	80.89	89.00	69.60
Optimal Platforms (UAS-ARFF)	38.72	59.40	87.86	59.78
Fixed-wing sUAS	35.42	63.32	216.25	164.74
VTOL sUAS	22.09	36.21	80.94	58.11
Electric sUAS	25.88	45.55	78.06	45.63
Internal Combustion sUAS	40.86	69.26	402.19	343.59

Theory of Operation

The creation of a theory of operation for each subject application analysis is critical to establishing relevant and applicable operational conditions and criteria. These steps are necessary to define specific operational environment details (launch, waypoints, and recovery positions/altitudes), directions (heading/bearing), and maneuvers types (launch, recovery, orbits, forward flight, and hover) incorporated into the simulation scenarios. The following represent adapted steps of the initial UAS-ARFF response theory of operation (as depicted in Figure 1; Terwilliger et al., 2015a):

1. Expedited (de-conflicted) deployment of initial UAS, concurrently with ARFF mobilization
2. Fly to accident scene (route to accident)
3. Establish sensing perimeter upon arrival at scene (enter orbit)
4. Gather information about scene; communicate information real-time to ARFF (fly orbit)
5. After designated number of orbits, return to base (RTB; exit orbit and enter return route)
6. Recover UAS platform (landing and recovery)

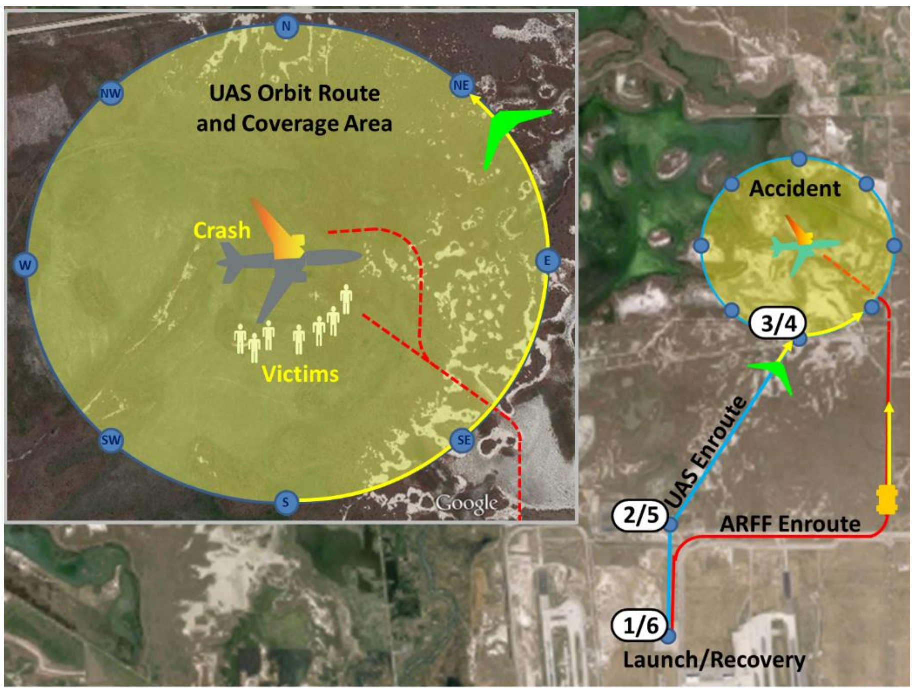

Figure 1. UAS-ARFF theory operation with inset depicting orbit and coverage area

Scenarios

To support development of the experimental scenarios (trials), fatal accidents within a 3.5 year period (1 January 2011 to 1 August 2014) and nationwide meteorological conditions were examined to identify relevant environmental and accident conditions. Critical factors of the accidents were identified and captured from accident reports in the National Transportation Safety Board (NTSB) Aviation Accident Database (2014). These factors included category of the aircraft (*airplane*), investigation type (*accident*), injury severity (*fatal*), and operation (*part 121, 125, 129,* and *135*). Those results that indicated the aircraft did not require ARFF response (e.g., no damage to aircraft reported or accident occurred greater than five-miles from the airport premise) were eliminated.

A total of seven accidents and associated airports were identified and examined. The details of each accident were captured, including aircraft type, heading, and distance; location and size of ARFF; unique geographic features of the environment; and weather conditions present. This information supported re-examination of the theory of operation and identification of individual extraneous control variables, including applicable ranges, for use in experimental trials. The variables were defined using conditions observed in the investigated accidents, national weather data, or unique to Salt Lake City (SLC) airport, the environment selected for use in this study. These values included accident position (within 0-5 SM of facility), operational phases of accident (taxi, takeoff, or landing), wind speed and direction (0-11kts; 0-359 degrees for taxiway or 315-45 and 135-225 degrees for takeoff/landing), crashed aircraft type (commercial, small taxi/passenger, or 20+ passenger), crashed aircraft heading (315-45 and 135-225 degrees), and origin. Randomization and subsequent logical selection were incorporated into the automatic assignment of extraneous control variables within the 30 scenarios. The wind speed was limited to a maximum of 11 knots, while heading ranges (excluding taxiway accidents) were set between 315 to 45 degrees (southern takeoffs/northern landings) and 135 to 225 degrees (northern takeoffs/southern landings), to align with mean weather conditions and features of the SLC airport. Available traffic directions and origin values were determined based on available runways (34L, 34R, 16R, and 16L) or randomly selected taxiway positions (16 total) and previously assigned extraneous control parameters (e.g., operational phase of accident, accident range, and assigned positions). For this iteration, the assumption was made that environmental conditions were acceptable to support UAS flight operations.

Application Analysis Framework

To perform the necessary experimentation, calculation, data logging, observation, analysis, and visualization an application analysis framework, termed capability analysis and effectiveness response for unmanned systems (CAERUS), was conceptualized and developed by the research team (Stansbury et al., 2015; Terwilliger et al., 2015a). This prototype framework is configured to unique applications for examination and measurement of simulated UAS operational effects on criterion variables, while providing management of extraneous control variables within a subject (simulated) environment. CAERUS requires creation and input of APMs, subject environment representative scenarios, applicable hypotheses, criterion, and external comparison values. CAERUS is also used to produce rudimentary visualization of each flight profile and path, calculated wind and flight maneuver effects (speed), consumption of power (endurance), distance determination (range), statistical analysis (analysis of variance [ANOVA]), and hypotheses testing results. The resultant information is used to assess applicability of a specific UAS platform configuration or category to perform the configured application, observe performance at individual flight segments, and generate recommendations based on outcomes of experimentation.

Calculations. It was necessary to define a series of constants for use across all experimental trials, including the position where the UAS is launched/recovered (altitude, latitude, longitude, and heading), and applicable automatic waypoint routing logic. The remaining details of the trial are calculated in series; accident details, UAS flight parameters, orbit locations, UAS flight visualization, orbit visualizations, airspeed calculations, maneuver calculations, endurance calculations, scenario calculations, and final results.

Accident details. The first set of calculations (unique to UAS-ARFF, adaptable to other applications) are performed to ascertain the position of the area of interest (accident) relative to the launch position, such as distance the UAS would fly if traveling in an uninterrupted path and distance conventional ARFF response needs to travel overland to reach a crash scene. The conventional ARFF response distance is determined by examining available roadways and paths on an external tool, such as Google Maps (2014), capturing measurement from the most applicable suggested driving route and distance, and manually entered. When no roadway or path is available, or the suggested route terminates prior to reaching the crash position (i.e., undriveable), the distance is calculated using an alternative measurement method, such as the measure distance feature (Google, n.d.) of Google Maps (2014), and then manually entered into the framework.

UAS flight parameters. The next series of calculations are performed to determine results of specific operational segments (phases) of the flight, including position and orientation of the aircraft, orbit attributes, and distances (from last point, from launch, to accident, to/from orbit entry/exit, and cumulative). The orbit radius is determined by calculating the distance of the orbit entrance from the accident position. Each of the successive orbit points are then calculated an equidistant value away from the center. A minimum radius required for maximum cruise speed is also calculated based on the highest cruise airspeed value of all the UAS models. If the minimum radius is not met, a new radius entry waypoint position, further away from the crash scene, is automatically calculated and assigned.

Visualization calculations. A series of calculations are performed to determine positioning and visualization of orbit points and flight path segments in the simulated environment. An orbit locations series is used to determine each of the orbit point positions based on known entrance point, radius, and position of the crash. A flight visualization calculation series is used to transpose latitude and longitude positions of relevant points and connecting flight path used in the scenario (origin, waypoints, and accident location) onto a chart for user review (requires manual verification). An orbit visualizations calculation series is used to transpose latitude and longitude positioning of eight successive orbit points (N, NE, E, SE, S, SW, W, and NW), connecting flight path, and accident location used in the scenario onto a chart for user review (requires manual verification).

Speed, maneuvers, and timing calculations. A further series of calculations are performed to determine the individual speeds, maneuvers effects, endurance values, and scenario timing of each platform type, sequentially, through the simulated scenario. An airspeed series is used to calculate the airspeed and relative ground speed of each UAS model for the flight segments, given a calculated difference between wind direction and UAS heading at each flight segment. The airspeed of the aircraft from launch (origin) to launch complete segment (first in series) uses documented maximum airspeed, while all remaining segments (i.e., enroute to remaining waypoints) use cruise speed of the platform. Dynamic wind was not modeled in this iteration; the direction and speed remain continuous throughout the trial regardless of altitude or location. A maneuver series is used to calculate changes in altitude, subsequent distance change due to altitude (trigonometric function) during aircraft transition between segments, and resulting duration required for each UAS model to perform the individual maneuvers (individual flight segments). An endurance series is used to determine propulsion power usage of each UAS model (for each flight segment and cumulatively), endurance remaining, and percent power remaining at the completion of each segment. A scenario calculations series is used to ascertain elapsed scenario time for each UAS model at the completion of individual flight segments and cumulatively for the entire scenario.

Final results. This final set of calculations (customized to application) is used to determine total distance traveled throughout the UAS-ARFF response effort (i.e., summation of distances flown), duration of operation, state of endurance (available or exceeded), state of range (available or exceeded), time required for response method to reach site, rank order of response times, time to site for direct travel (i.e., direct line from launch to orbit entry over accident), rank order of direct response times, mean UAS response time, and percentage difference between the calculated conventional ARFF response and mean UAS response. The time of conventional ARFF response (i.e., control treatment) is calculated using a formula developed by the RAND Institute to approximate fire apparatus travel time (based on 35 miles per hour [MPH] average speed) where the response time is equal to 1.7 times the distance, which is then added to .65 ($T = .65 + [1.7 \times distance]$; Insurance Services Office, n.d.; Kolesar, 1975; Kolesar & Blum, 1973). As some of the distance may be un-navigable using road vehicles, it may be necessary to calculate the response time when hiked. To calculate this value the total undriveable distance is divided by an average hiking rate of 4.5 MPH and then combined with the driven response time.

As each scenario is subject to variation of accident distance, based on randomized crash placement, the definition of a measure comparable among all scenario and treatments was necessary. A variable termed response rate (in MPH) was created and calculated to represent a metric that varies based on model performance within each scenario response, but is not subjective to changing distance among scenarios. The response rate for each model is calculated by dividing distance traveled by the response speed to reach the accident scene. The final product response rate of each treatment was used in the final statistical analysis and comparison of the seven treatments (UAS models and ARFF).

Verification. The verification of the framework was accomplished by comparing individual calculated derived positioning, maneuvers, and timing results from CAERUS to calculated results from external sources to identify differences (deltas), error values, and error rates. The external sources used included calculators for bearing and distance (GeoMidpoint.com, n.d.; Hedges, 2002; Proxim Wireless Corporation, n.d.); unit conversion (Google, n.d.); geometry and wind effect (1728 Software Systems, n.d.; Computer Support Group, n.d.; Leidos, n.d.; Pythagoras-Calculator, n.d.); and time, speed, and distance (Computer Support Group, 2011). The exhibited error rates among calculations in the CAERUS framework was .06 percent for bearing (heading), .56 percent for distance, 1.47 percent for speed, .99 percent for scenario (elapsed) time, 2.39 percent for duration, and a mean error rate for all calculations of 1.12 percent. The majority of error observed in calculation was determined to result from external calculation tool imprecision as most featured less (two) decimal place precision as the framework (four decimal place precision).

UAS Flight Visualization. A custom software application, titled Google Earth Waypoint Flight (depicted in Figure 2), was developed by the research team to input subsequent APM, routing, and flight parameters from the application analysis framework to create visual narratives of individual UAS flights. These visual narratives are used to perform more in-depth scene exploration (observation) and gain an improved understanding of implications associated with use of UAS to perform the given function within the subject environment. The tool was developed using C# and features use of the deprecated Google Earth application program interface (API; no longer available after December 12th, 2015; Google Developers, 2015). The application provides a series of user options, such as onscreen depiction of route lines, three-dimensional (3D) buildings and trees, visual identification and tracking of orbit center point, in addition to ability to manipulate extraneous control parameters (e.g., wind speed and direction). Options for a replacement mapping and visualization solution are being explored, including commercial simulation image generators (IGs) and other online tools.

Figure 2. Flight visualization application

RESULTS

Upon completion of the experimentation, statistical analysis was conducted on the data produced from the 30 trials. The initial evaluation indicated that several platforms categories exhibited faster response speed than conventional ARFF (32.09 MPH); tube-launched (49.92 MPH), internal combustion sUAS (45.39 MPH), optimal platforms (42.31 MPH), and fixed-wing sUAS (38.90 MPH). The mean response speeds, along with other descriptive statistics, for each UAS type and conventional ARFF are depicted in Table 2.

Table 2. Descriptive statistics for response speeds

Treatment Type	*n*	Mean	SD	Variance	Range
Tube-launched Platforms	30	49.92	8.09	65.43	39.43-72.81
Optimal Platforms	30	42.31	6.99	48.84	32.73-58.81
Fixed-wing sUAS	30	38.90	7.38	54.40	28.95-56.63
VTOL sUAS	30	22.57	6.47	41.86	13.40-38.26
Electric sUAS	30	27.29	6.83	46.70	17.82-43.69
Internal Combustion sUAS	30	45.39	7.69	59.20	35.32-66.48
Conventional ARFF	30	32.09	3.88	15.03	20.69-43.07

During creation of the six new APMs there was potential for individual UAS platform configuration samples to be used in multiple treatments, when selection criteria overlapped. For example, the same UAS could be included in the optimal, electric sUAS, and fixed-wing sUAS categories. However, there was no overlap among individual experiment results (individual treatment response speeds were independent [mutually exclusive]), representing the data that were statistically examined in this study. The resultant data were tested for the assumptions of ANOVA yielding normal distributions, albeit marginally in some cases, and samples were confirmed to be independent cases. A Levene's test indicated medium deviation from homogeneous variances (p = 0.026; Field, 2009; Levene, 1960). As a precaution to these aforementioned issues, a Welch's ANOVA was conducted, while Games-Howell *post-hoc* testing was employed in accordance with the guidance of Field (2009).

Results from the Welch's ANOVA indicated significant differences among groups, $F(6, 203) = 58.423$, $p < 0.01$, $\eta^2 = 0.65$. A null hypothesis that UAS are not capable of faster response than conventional ARFF was rejected (further corroborating results of initial experiment analysis; Stansbury et al., 2015; Terwilliger et al., 2015a). According to the results of the *post hoc* testing, all types of UAS were statistically significant and differed from conventional ARFF, with electric sUAS exhibiting the largest significance (p = 0.025). When comparing the optimal platforms with other descriptors, this group was superior to all except fixed-wing sUAS (p = 0.529) and internal combustion sUAS (p = 0.668), indicating that these subsets would be most likely attributes of the most compatible systems. The types of sUAS that had the largest mean differences in response versus conventional ARFF were tube-launched (-17.82), internal combustion sUAS (-13.29), and the optimal platforms (-10.21). The observed variance within UAS treatments was determined to be a result of differing wind conditions (heading and speed) present in the scenarios and their effect on platforms; when wind speed was minimized to zero, in all scenarios, variance levels reduced dramatically (tube-launched [s^2=8.56], optimal [s^2=3.65], fixed-wing sUAS [s^2=8.56], VTOL sUAS [s^2=1.27], electric sUAS [s^2=2.49], and internal combustion sUAS [s^2=7.14]).

DISCUSSION and RECOMMENDATIONS

The application of UAS outside the military realm is expanding dramatically as need, system performance, and technological capability evolve. Selection of a platform with inadequate capabilities and unsuitable characteristics can be both costly and disastrous to agencies, companies, and industries investing in this technology, especially when the objective is increased efficiency and enhanced safety. A number of fields, such as filming, energy, real estate, agriculture, and e-commerce/logistics (e.g., Amazon/ Kiva Systems), are actively recruiting talented professionals (including M&S subject matter experts) to support economic UAS endeavors, while advocating for enactment of FAA regulation for legal use within the NAS (Devaney, 2014; Terwilliger, 2015). In the case of ARFF application, selecting a platform not ideal or optimal in configuration can result in extended response time, degraded SA, diminished safety, and increased loss of life in emergency response situations (i.e., impede existing response capability; Terwilliger et al., 2015b). ARFF personnel require platforms that can be deployed with minimal preparation; operate under a variety of dynamic environmental conditions; arrive on scene quickly; remain operational until scene can be secured and proper resources allocated efficiently; and are capable of carrying sensors that can transmit information back to first responders in a timely and efficient manner, without causing undue burden (i.e., enhance rather than reduce effectiveness of response; Terwilliger et al., 2015b).

The optimal platform category examined in this study represent those sUAS with documented attributes meeting base recommended requirements for initial response, previously discussed (Terwilliger, et al., 2015a). The data analysis indicated this category produced superior performance, when compared to conventional ARFF response. Yet, it did not perform significantly differently than fixed wing sUAS or internal combustion sUAS platforms. This indicates any of these three UAS platform types are capable of arrival on scene significantly faster than conventional ARFF, which would provide ARFF personnel the ability to collect data and plan allocation of resources before arriving on scene. However, the individual fixed-wing and internal combustion sUAS platforms may have additional use considerations, such as longer initialization (launch) time and increased maintenance complexity, which could limit suitability for UAS-ARFF application. Such limitations should be examined and addressed in subsequent analysis. The ability to capture advanced information, ahead of arrival of a conventional ARFF response, is anticipated to support more efficient deployment of resources, enhanced SA, and safer, less chaotic operating conditions at the scene.

Although this research featured UAS-ARFF response as an application case, CAERUS can be adapted in a similar manner for any commercial, industrial, or civilian application analysis to determine platform compatibility with tasking and application. By utilizing the same UAS platform functional model parameters (attributes) and customizing the framework to incorporate different (application unique) tasking needs and environmental factors (extraneous control variables), CAERUS can be used to generate efficient and accurate determination of platform performance; thereby saving money and resources by selecting, adapting, and employing the most appropriate UAS platform from initiation. These potential benefits, available using computation and analyses, such as M&S, provide improved awareness of system limitations, constraints, performance, applicability, and visual narratives of use, prior to acquisition and operation (Terwilliger, et al., 2015a).

Future related research should be multivariate in nature, taking into account not only speed, endurance, and range of existing UAS platforms (Terwilliger et al., 2015a), but also other relevant variables that add to the fidelity and effectiveness of the M&S scenarios. It is suggested that future research and subsequent iterations of CAERUS address potential effects of visibility, dynamic wind conditions, precipitation, route accuracy, time to deploy, maneuver fluctuations, and operator knowledge, skills, and abilities (KSA) requirements (Ison, Terwilliger, & Vincenzi, 2013; Terwilliger et al., 2015a). Additional goals for future research should include refinement of models; expanded trials at different locations under varying, more accurate environmental conditions; consideration of other factors, such as pricing and reliability; effects of varying payload (sensors), command, control, and communication (C3), and support elements; external validation using actual UAS platforms; development of UAS performance rating standard; and examination of methods to identify appropriate training requirements and delivery approaches, such as live, virtual, and constructive (LVC), for the acquisition, application, and assessment of requisite operator KSAs (Ison, Terwilliger, & Vincenzi, 2013; Terwilliger et al., 2015a).

CONCLUSION

The methodology and results outlined in this study are originative and foundational for UAS stakeholders to evaluate, measure, and select specific platforms best aligned with proposed missions. It is paramount that UAS manufacturers and users alike have the most accurate information possible to make such critical decisions. This data could be used to guide UAS designers to modify or create platforms to better suit the user through improvements to systems engineering, as well as designing more robust platforms. For users, this information can support elimination of waste (time and resources), avoiding misguided purchase decisions, or problematic operations of the platform. The current study is guided by and builds upon a wide range of exigent literature, including regulatory guidance, typical applications, as well as in-depth investigation into the evaluation of performance of UAS in a variety of scenarios (Devaney, 2014; FAA, 2015a; Stansbury et al., 2015; Terwilliger et al., 2015a). By using such a building block approach in the conduct of the current study, a wide range of potential industry and defense UAS applications can utilize and benefit from the results. In the case outlined in this paper, CAERUS was able to establish the ideal types of UAS to perform ARFF functions through the use of modeling and simulation. By identifying the challenges to specific UAS operational uses, e.g. wind, and through the improvement of the modeling and simulation methods used in this research, continuous enhancement to CAERUS and its associated benefits will be able to occur.

ACKNOWLEDGEMENT

This work was made possible because of prior work involving our colleagues and research collaborators, including Dr. Ken Witcher (ERAU-W, Dean of College of Aeronautics), David Thirtyacre (ERAU-W), Dr. Rene Herron (ERAU-W), and Dr. Adeel Khalid. Additionally, recognition is due to Dennis Shockley, I/ITSEC Emerging Concepts & Innovative Technologies subcommittee representative, for providing guidance and support as "birddog" for this paper.

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