Research Article

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Consumer Multirotor sUAS Evaluation and Rating

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Abstract: Terwilliger B, Thirtyacre D, Kleinke S, Burgess S, Ison D, Cerreta JS and Walach C. (2016). Consumer multirotor sUAS evaluation and rating. *International Journal of Unmanned Systems Engineering*. ***4***(2): 1-18. A substantial shift in the use of unmanned aircraft systems (UAS) and integration into the U.S. National Airspace System (NAS) is beginning to occur, including wider application and operation under Federal, State, and local regulations. The Federal Aviation Administration (FAA)'s small UAS (sUAS) certification and operation rules are expected to further increase operational accommodation, oversight, and tracking, as entrepreneurs, manufacturers, and researchers pursue innovative unmanned system technology development. A research team, composed of students and faculty, at Embry-Riddle Aeronautical University, developed and conducted a mixed-methods research approach, featuring sequential explanatory design, review of published performance data, and operational testing of a series of common consumer multirotor sUAS to identify and analyze critical evaluation criteria. This project required the identification and use of a common set of evaluative measures, indicating system suitability, performance, and cost-effectiveness. The study featured the collection of quantitative and qualitative data in series, analyzed independently and then merged for final analysis to compare individual measures representing capability with subjective assessed quality ratings to determine an overall level of platform suitability to a novice user. The data associated with these measures were captured through investigation, inspection, and operational testing of each platform. The individual scores from the assessments supported the calculation of scores and ranks for the sUAS, from most suitable to least, in addition to most operationally and cost effective. Use of such measures may serve as the basis for future assessment to better understand consumer sUAS applicability and capability, while ensuring the continuation of safety, efficiency, and effectiveness of operations conducted in the NAS. The details of this project, including research methodology, results, implications, and recommendations, are presented and discussed in this paper.

Keywords: Consumer multirotor, sUAS, sUAS acquisition, sUAS evaluation, sUAS novice users.

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I. INTRODUCTION

A substantial change in the use of unmanned aircraft systems (UAS) and their integration into the U.S. National Airspace System (NAS) is beginning to occur, including wider application and operation under Federal, State, and local regulations. The Federal Aviation Administration (FAA)'s Part 107 - small UAS (sUAS) certification and operation rules [1] are expected to further increase operational accommodation, oversight, and tracking, as entrepreneurs, manufacturers, and researchers pursue innovative unmanned system technology development. However, despite recent technological and regulatory advancement, concern for irresponsible operation of sUAS (55 pounds and under) continues to increase [2-5]. The projection that more than 2.5 million such platforms are currently operating in the NAS, with potential growth of up to seven million by 2020, has far reaching implications for this evolving, $100+ million industry [6-8]. The development of a common set of sUAS evaluative measures, indicating system suitability, performance, and cost-effectiveness, can help novice and experienced operators better appraise consumer system applicability and capability to ensure safety, efficiency, and effectiveness in planned operations.

The total population of available sUAS is rapidly expanding (approximately 650+) [9] and includes substantial variation in terms of design, performance, and system attributes [10-11]. The population is composed of fixed-wing, multirotor, and hybrid platforms weighing up to 55.00 pounds (maximum gross takeoff weight [MTOW]; mean of 17.52 pounds), featuring use of internal combustion or electric propulsion and capable of achieving speeds to 248.38 knots (mean 48.77 knots), maximum altitudes up to 25,000 feet above mean sea level (MSL) (mean 10,755.63 feet MSL), endurance to 40.00 hours (mean 2.03 hours), operational ranges to 2,248.37 statute miles (SM) (mean 101.65 SM), payload capacity up to 41.50 pounds (mean 6.53 pounds), maximum wind limits of 150 knots (mean 24.46 knots), and acquisition costs to $3.20 million (USD) (mean $71,034.88 USD) [12]. Understanding the implications of such capabilities and traits presents a challenge to those inexperienced with the safety precepts, rules, and operational criteria integrated across aviation culture and the regulatory environment [13-14].

A growing segment of early technology adopters have begun acquiring and using sUAS without prior exposure to the resources, education, or insight available to individuals experienced with professional or recreational operation of aviation assets [15-17]. In support of increasing interest, a number of consumer sources (e.g., technology and electronics blogs and magazines) have begun reviewing features and published performance of multirotor sUAS [18-20], a design configuration popular among this segment of users; such materials also often include guidance relating to limited use cases and operational conditions [21]. While these resources can provide useful comparisons of technological attributes and common sense application, they tend to not sufficiently cover those features and capabilities essential to continued aviation safety and compliance with FAA regulatory criteria (e.g., operational and performance limitations; available support; and human factors considerations, including crew resource management, control interoperability and interface, and remote pilot sense and avoidance potential).

There is an exhibited need to create a repeatable and consistent evaluation method, appropriate to consumer-level sUAS, supporting the production of quantitative and qualitative, evidenced-based assessment featuring the incorporation of critical insight and compliance with aviation safety and regulatory requirements. Effective sUAS evaluation and rating is envisioned to support the growing user population in assessing options, appropriate to their skill level, knowledge, and experience, while improving the potential for operational requirements observance. This study was conducted to identify and compare individual sUAS performance measures, representing platform capability (i.e., quantitative), with subjective assessed quality (qualitative) ratings to create an effective review strategy. The primary focus was placed on the capture and analysis of data to identify end user (i.e., novice remote pilot) suitability, with secondary goals to identify overall performance relative to similar systems and cost-effectiveness based on measured performance and financial investment. The resulting assessment schema, initially presented in the ERAU-Worldwide *Small Unmanned Aircraft System Consumer Guide* [22], is intended to serve as a standard for future consumer sUAS evaluation and rating, with the further results, observations, and details presented and discussed in this paper.

II. Methodology

A research team consisting of students and faculty across Embry-Riddle Aeronautical University (ERAU; Worldwide and Daytona Beach campuses) developed and conducted a mixed-methods (i.e., sequential explanatory) research strategy to examine a series of consumer multirotor sUAS (instruments). The purpose was to measure and identify suitability of the systems for use by novice remote pilots, as well as the overall performance and cost-effectiveness of each system. The study featured the collection of quantitative and qualitative data in series, analyzed independently and then merged for final analysis to compare individual measures representing capability with subjective, assessed quality ratings to determine an overall level of platform suitability to an end user (i.e., novice). The data associated with these measures were captured through investigation, inspection, and operational testing of each platform. The individual scores from the assessments (quantitative and qualitative) were used to calculate a score and ranking for suitability, system performance, and cost-effectiveness.

This project required the collection of published performance (quantitative) data for consumer multirotor sUAS, based on a predefined set of selection criteria; generation of funds through a crowdfunding campaign, including donations of systems for inclusion in the testing [23]; development and approval of an *Operational Test Plan* [24]; and the performance of operational assessment of acquired sUAS, as a group in Daytona Beach, FL. The acquired sUAS were operationally tested indoors and outdoors, in accordance with approved conditions outlined in the test plan; under provisions of the Nevada Institute for Autonomous Systems (NIAS; FAA-designated Nevada UAS Test Site) public certificate of waiver or authorization (COA); as well as Federal, State, and local regulations. The testing event featured detailed examination of each system, operation as suggested by the manufacturer (operational ease), review of system assembly (construction quality), comparison of published performance to operational experience (availability and accuracy of reported values), and use of available operator support resources (user support).

2.1 Research Design

A mixed-methods research approach, featuring sequential explanatory design, was selected to gain a comprehensive understanding of the underlying factors affecting potential usability of popular commercial-off-the-shelf (COTS) multirotor sUAS. The research design involved the identification, collection, and analysis of quantitative data first, for use in the later capture, analysis, and interpretation of qualitative data. The quantitative aspect of the research design was supported through the investigation, categorization, and recording of publicly published sUAS performance data and specifications. The qualitative aspect was developed after initial review of the quantitative investigation and featured the performance of sUAS operational planning and testing activities, coupled with researcher evaluative assessment. This process supported exploration of the problem from multiple perspectives, while providing a mechanism to update and revise the strategy [25] to meet goals, despite potential changes to regulations, advances in technology and operational methods, budgeting, and availability of sUAS platform samples (i.e., system selection and acquisition).

2.1.1 Research Metrics

The research design for this study featured the definition, capture, and analysis of a series of common measures. These measures, both quantitative and qualitative, were respective of system performance and subjective assessment. While the measures are not an exhaustive collection, identifying all possible or unique attributes of a consumer sUAS, they are indicative of common properties requisite to determine capability, limitations, quality, and comparative performance. The metrics (values), captured throughout the progression of the research, were used to calculate the system evaluation scores and ranking.

Quantitative Metrics. The quantitative metrics represent the measurable properties and performance capabilities of each sUAS examined. The majority of measures were captured directly from public sources, prior to performance of operational testing, and used in the operational and safety management planning. The following represent the quantitative metrics featured in this research:

- *Maximum Speed* – upper limit speed of the aircraft (knots)
- *Endurance* – upper limit of operational time of the system (minutes)
- *Payload Capacity* – lifting capability of the aircraft (pounds)
- *Camera Quality* – sensor fidelity of video (vertical pixel resolution; *p*) and still imagery (megapixels; *MP*)
- *Pricing* – complete system cost, including requisite operational elements, including aircraft, controller, second battery, charger, and transport case (maximum $3,500 USD)
- *Communication Range* – upper limit functional distance between aircraft and controller (feet)
- *Utility* – number of defined applications supported (training, aerial filming, research, and recreation; 4/4, *100%)*
- *Critical Metrics* – percentage of quantitative performance metrics, available from public sources (7/7, *100%*)

Qualitative Metrics. The qualitative metrics represent subjective assessment of critical system traits, captured through inspection, investigation, operational assessment, and analysis. The following represent the qualitative metrics featured in this research:

- *Construction Quality* – workmanship and caliber of construction, assembly, and durability of the system and its components
- *Operational Ease* – intuitiveness of operation and ability to support wide range of users, including novices
- *Availability and Accuracy of Reported Values* – completeness and consistency of published information
- *User Support* – resources, tools, and guidance information available

Each qualitative measure was evaluated and scored by student and faculty researchers, in accordance with detailed assessment and scoring criteria (i.e., rubric; from *0-100%)* contained in Tables 1 - 4. A limited degree of automatic functionality was also examined in each assessment, however a detailed comparison of such functions among the sUAS platforms was not performed.

2.1.2 sUAS Sample Selection

The decision to focus on a subset of the larger sUAS population, consumer multirotor sUAS, was made to support investigation of systems commonly purchased by a rapidly growing user base (i.e., novices for recreation, aerial filming, training, and research), as well as practicalities of system acquisition and testing. A series of sample selection requirements were established at the start of the project, based on commonly observed attributes among such users, to isolate the subset population from the larger and meet the previously described goals. These requirements included criteria based on cost, system design configuration, functional operational support, and availability. A maximum price point of $3,500.00 (USD), including equipment needed to operate (e.g., sUAS, second user-replaceable battery, charger, and transport case), as well as design and configuration requirements that the sUAS be an electric, multirotor system with a MTOW of 7.50 pounds or less, were chosen based on review of example systems, consistency in performance measurement and comparison, and utility necessary to support repeatable operation. To support the primary anticipated audience and target user, only COTS options available from retailers (e.g., hobby and department stores or online retailers) were included in the study; no custom options solicited directly from manufacturers were included based on substantial cost, function, and design variation associated with such systems.

Table 1: Qualitative – Construction quality assessment criteria

Construction Quality: *The workmanship evident in the construction and assembly of the systems and its OEM components. This evaluation consists of examining durability of construction materials, ease of maintenance and calibration, and precision of assembly. Third-party components are not accessed in this evaluation.*

Construction Quality	Description
High (76-100)	High degree of quality is evident. Construction materials are highly durable and able to withstand unexpected stresses of repeated operation. System has been designed to support inspection, overhaul, repair, preservation, replacement of parts, and preventive maintenance (e.g., component replacement). Components are fitted together with no movement or gaps, except where required.
Medium (51-75)	Medium degree of quality is evident. Construction materials are somewhat durable and able to withstand expected stresses of operation. System has been designed to accommodate some maintenance (major component replacement). Components are fitted together with slight movement or gaps, except where required.
Low (1-50)	Low degree of quality is evident. Construction materials are not very durable and may not withstand stresses of repeated operation. System has been designed to accommodate little to no maintenance and components are not replaceable. Components are fitted together with significant movement or gaps, except where required.
None (0)	No quality of construction is evident in the design and manufacturing of the system.

Table 2: Qualitative – Operational ease assessment criteria

Operational Ease: *The ability of the system to be operated by a wide range of operators from inexperienced first-time operators, to experienced and trained manned pilots. This evaluation consists of examining the intuitiveness of operator controls and their placement, ability to vary response to suite proficiency, and integration of easy to operate automatic features in the operator interface.*

Operational Ease	Description
High (76-100)	The design of the control interface exhibits significant thought towards supporting a wide range of operators with responsiveness of the system configurable to match the ability of the operator. Important information or controls are easy to reach and use. Efficiency and safety controls are provided, such as heading and/or altitude hold, return to home, and automatic landing.
Medium (51-75)	The design of the control interface exhibits some thought towards supporting a wide user (operator) base with responsiveness of the system being adjustable. Important information or controls are somewhat easy to reach and use. Limited efficiency and safety controls are provided, but may require complex operation or configuration to enable.
Low (1-50)	The design of the control interface has been developed for a single experience level and provides very little to no customization. Important information is not present and/or controls are not easy to reach or use. No efficiency and safety controls are provided.
None (0)	This system provides no user control for operation.

Table 3: Qualitative – Availability and accuracy of reported values assessment criteria

Availability and Accuracy of Reported Values: *The availability and accuracy of performance values (metrics) specified by the vendors or third-parties, which are used to analyze and justify selection or use of a platform and perform detailed flight planning and safety analysis. This evaluation consists of examining critical performance values identified in associated marketing or support literature (e.g., maximum speed, endurance, payload capacity, camera quality, and communication range) and comparing to results observed throughout repeated operation.*

Availability and Accuracy	Description
High (76-100)	The information provided for the system is complete and accurate. The system operated in accordance with published parameters and in some cases, better than advertised.
Medium (51-75)	The information provided for the system is partially complete and accurate. The system operated closely to published parameters.
Low (1-50)	The information provided for the system is incomplete and inaccurate. The system did not operate as advertised.
None (0)	No information was available for the system, comparison was not possible.

Table 4: Qualitative – User support assessment criteria

User Support: *The level of support available to an operator. This evaluation consists of examining the amount and quality of media, documents, specifications, training, and user communities (e.g., forums).*

User Support	Description
High (76-100)	The level of support is very high, with detailed operational and maintenance guidance provided. There is a dedicated website, featuring documentation downloads, user groups for collaborative discussions and queries, and dedicated service personnel to address inquiries.
Medium (51-75)	The level of support facilitates finding answers to inquiries through a FAQ, presentation of system specification values, with some operational and maintenance guidance provided. There is a dedicated website that provides operator access to some relevant information and/or guidance.
Low (1-50)	The level of support facilitates finding answers to inquiries through a FAQ, presentation of system specification values, with some operational and maintenance guidance provided. There is a dedicated website that provides operator access to basic system specifications.
None (0)	No support is available to operators, the system is only advertised through resellers with availability of information subject to considerable change.

2.1.3 Research Assumptions

The development of this study also required consideration and identification of several assumptions, derived from the research goals, sUAS sample selection criteria, and observations made from review of literature and incorporation of past operational experience. The availability and pricing of several common system elements used to enhance or augment control and function, such as a laptop computer, smart-device (tablet or phone), and high definition (HD) camera (e.g., GoPro) were assumed and not included in cost calculation or analysis. The registration and operation of the sUAS, in accordance with applicable laws and community-based safety practices, was also assumed. Finally, if a quantitative measure was either not applicable or available it was treated as a zero (0.00) in scoring calculation. However, if the measure was captured or derived through testing, it was accordingly analyzed and acknowledged in the subsequent presentation of results (e.g., observed maximum speed).

2.2 Safety Analysis

Safety Risk Management (SRM) was used to analyze systems, procedures, and processes to determine risks associated with planned flight operations. The team adapted a SRM process from the FAA in *Advisory Circular (AC) 120-92B* [26] to analyze the proposed operations and sUAS, identify hazards, analyze and assess risks, implement controls, and evaluate the controls for potential effectiveness. The process was focused on identifying, categorizing, and addressing all possible hazards that could be encountered during the operational data collection phase of this study. An analysis of risks, based on vehicle weight, functional capabilities and completeness of system-level documentation, were affinitized into three groups; simple, intermediate, and complex. The team identified 48 hazards from UAS operations, mishaps, and hazard reports, including past experiences, applied to this operation.

Safety Risk Analysis (SRA) processes were employed to analyze the hazards for possible risks and the controls were developed to mitigate those risks. The team used the SRA process to examine the likelihood and the severity of injury to participants and bystanders, as well as damage to equipment and property, involved in the study. Each hazard was assigned an overall risk level from the likelihood of occurrence being improbable (1) to frequent (5) and a severity level from negligible (A) to catastrophic (E). The evaluation of risk levels for each hazard provided a priority to mitigate any risks not at an acceptable level. Both indoor and outdoor operations were examined to identify pre-mitigation hazard outcomes. If the risk levels were acceptable or adequate controls employed mitigated the hazards to acceptable levels, the mitigation process was considered complete and incorporated into a mission-specific risk assessment worksheet.

The outcomes from the risk analysis from the identified hazards indicated that risks ranged from low (2D) to medium-high (2B) without mitigation. Seven specific hazards were considered low (2D) risk, seven in medium-low (2C and 3D) risk category, and four in medium-high (2B) risk category before mitigation strategies were implemented. Many hazards were based on the ability to control aspects of the operational environment (e.g., weather and foreign object debris). An implementation of controls measures, including NIAS trained/approved Pilot-in-Command and Visual Observers, site surveys, pre-flight inspections, checklists, observation, flight course changes, verbal warnings, wearing of safety apparel, and safety briefings, mitigated all hazards to a low level (2D or 2E).

A Safety Review Board consisting of members from ERAU’s aviation safety management team, College of Aviation technical advisors, and the research team convened to examine the mitigated hazards. The Board reviewed each hazard, pre-mitigation risk levels, mitigation strategies and controls implemented based on criteria established by NIAS, and the resulting residual risk levels. Based on these results, and concurrence with the Board, the overall Assessment Risk Index was determined as “low” enabling the Chairman of the Flight Department as the appropriate approval level. The flight operations were preceded by a mission briefing to the indoor and outdoor team members to communicate the day’s operations, purpose, assessed risk levels, and emergency response actions. A risk assessment worksheet was used to record and summarize the residual risks based on current and forecasted conditions for the day. The residual risks could not exceed the Board approved level of low without escalating to the next higher accountable level, should the level increase to “medium”. Throughout the flight operations period, the residual risk levels remained at low levels.

2.3 sUAS Assessment

Assessment of the 12 subject consumer multirotor sUAS was conducted in three phases: (1) investigation and capture of published performance data, (2) planning and performance of operational flight testing, and (3) analysis of captured data to calculate evaluative scores and ranking. The following subsections contain the details of each respective phase.

2.3.1 Investigation and Capture of Published Performance Data

Performance data was captured by mining manufacturer websites and associated operational or guidance literature (e.g., user manuals or specification sheets). During the data collection process, it was discovered that the performance data made available by manufacturers was inconsistent. For example, Yuneec provides significant technical specifications for their Typhoon on their website. User documents for the Typhoon were lacking however, but additional guidance was found to be available online [27]. Contrarily, the Elanview website provided minimal useful information on their Cicada sUAS and the documentation accompanying the system was minimal, making a priori assessments challenging [28]. The inconsistent nature of data availability and lack of standardization among manufacturers makes it difficult for the consumer and researcher alike to be able to evaluate the expected performance parameters of different sUAS. Perhaps more problematic is the inability to make comparisons among sUAS models based upon available performance data. The current unavailability of such data may be a factor of sUAS being an emerging consumer technology, with manufacturers restricting access to protect their intellectual property, unique design attributes, or competitive advantage. However, this practice is contrast to manned aircraft as manufacturers of these aircraft provide extensive performance information and is generally analogous among types and models of aircraft [29-31].

Detailed technical information was not available within the supplied operation manuals for some sUAS examined. In cases in which manufacturer resources did not provide adequate information, either the manufacturer was contacted for additional information or third party empirical data was utilized. This process mitigated some of the missing performance metrics. Data sets were organized in preparation for comparing with subsequent flight testing to assess actual performance in typical, ambient conditions. Clearly, the varying obtainability of performance data from manufacturers complicates consumer assessment, comparison, and purchase decision making. This is critical to note that the cases of scarce data may lead to users to purchase a system that is incompatible with their skill level and intended types of operations. As the sUAS market matures, it is hoped that manufacturers will provide specifications and performance data consistent with that which is provided for manned aircraft. Moreover, standardization among sUAS documentation, common among manned aircraft, would not only be helpful to the user, but has potential to enhance operational safety [30].

2.3.2 Operational Planning and Testing

For the operational test phase, a standardized test sequence was developed for the two operating environments, indoors and outdoors. The primary emphasis during development was an optimized flow that allowed parallel acquisition of quantitative and qualitative data, while maximizing the number of individual data points captured within the lowest expected flight endurance of all 12 sUAS platforms examined in the testing. This test sequence was incorporated into a standardized checklist, featuring aircraft pre-flight inspection (Fig. 1), which was followed repeatedly for each individual platform test. Therefore, the established flight profile mirrored a functional check flight as known from operational testing of manned aircraft.

Fig. 1: Pre-flight inspections of sUAS
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The operational system evaluation and flight testing was preceded by an in depth theoretical familiarization with each platform, based on all available technical and support information. A pre-operation examination, featuring common sUAS knowledge and questions tailored to each platform, was administered to ensure that all team members possessed a minimum standardized system knowledge pertaining to that platform and the planned operations. The flight performance ability of each student remote pilot was also assessed, prior to the start of operation flight testing, using the *RealFlight 7.5 radio control flight simulation* application [32].

In addition to the personal required to conduct flight operations under the NIAS public COA (i.e., Pilot-in-Command and Visual Observer), each test event featured a minimum team consisting of a checklist inquirer and a record keeper to support the remote pilot. Additional assistance was available to backup record keeping tasks and assist with support operations, such as safety observation, battery charging, system assembly and setup, data upload and download, and research of technical information. For the assessment of maneuver precision, station keeping, and camera tracking, as well as evaluation of the quality of the optical camera system (if available), a set of standardized markers and targets (horizontal and vertical) were employed at the test sites. The indoor environment additionally included boundaries and markers (i.e., orange cones) for the establishment of safety zones (Fig. 2).

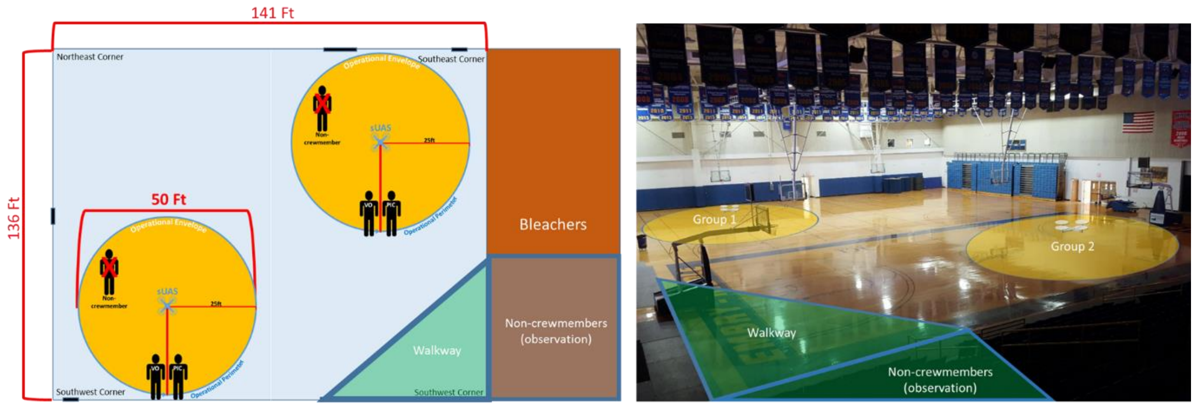

Fig. 2: Depictions of safety zones inside ERAU-DB Field House (indoor testing location)

To confirm previously collected performance data, a mobile measurement device (e.g., handheld Doppler-based speed measurement tool; see right-most image in Fig. 3) was employed outdoors on predefined flight track portions (e.g., low altitude, to and from the speed measurement tool, based on Doppler limitations) to improve measurement accuracy and consistency. To ensure elimination of ambiguities (e.g., sUAS rotor blades registering during measurement) and establishment of reliability of measurements, each system was tested at least twice in accordance with a full test profile, alternating the remote pilot between each test to control for validity of results and observations. In addition, individual profile aspects were repeated and confirmed from multiple remote pilots, obtained when unexpected or peculiar behavior was observed.

Fig 3: sUAS operational testing, indoors and outdoors
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2.3.3 Data Analysis

The data produced from the review of published performance and operational testing were captured and stored for categorization and analysis. The quantitative data, derived from public sources were used to identify critical parameters for use in both operational planning and development of the qualitative assessment rubric. The mean, minimum, maximum, and optimal values for each platform and measure were calculated and then used to determine ratings, scores, and rankings. Each value represents either an actual published or resultant (i.e., observed and recorded during operational testing) measurement, while the calculated rating indicates percentage of an optimal value (i.e., maximum or minimum observed, reported, or achievable; *eqs.* 1 & 2).

Individual sUAS measure score = (sUAS measure value / Optimal measure value) x 100% **eq. 1**
Individual sUAS pricing score = (1 – [sUAS cost value / 3500]) x 100% **eq. 2**

The ratings were used in the calculation of three scores: (1) novice suitability, (2) total system performance, and (3) cost-effectiveness. Each score represents the result of weighted calculation in relation to the entire sample population (*N*). The *Novice Suitability Score* indicates appropriateness of the sUAS for a novice remote pilot, as well as measures of useful functionality and quality; it is calculated by averaging individual rating scores of those measures essential to a users' experience (i.e., endurance, camera quality, pricing, construction quality, operational ease, accuracy, and user support). The *Total System Performance Score* represents the overall capability and effectiveness of a sUAS, in relation to all examined measures; calculated by averaging all weighted ratings. The *Cost-effectiveness Score* represents a performance investment return ratio, given purchase price (*eq.* 3), and indicates the cost per percentage point of equivalent performance among the sample population. For example, a score of 10:1 indicates that each percent of effective performance costs $10.00 (USD), while 50:1 reflects a cost of $50.00 (USD) per point, regardless of the total percentage points associated with the system.

Individual sUAS cost-effectiveness = (sUAS price / sUAS Total System Performance score):1 **eq. 3**

The number of samples (*n*) for each measure were also recorded, including total number reported for quantitative measures to calculate a reporting percentage (*N Reported*).

III. RESULTS

The results of the data analysis provide substantial insight relating to consumer multirotor sUAS categorization, assessment, and performance. Table 5 contains the mean, maximum, and minimum values, observed and published, in addition to the *n*, and *N Reported* for all the quantitative measures.

Table 5: Quantitative data results

Measure	Mean	Maximum	Minimum	n	N Reported (%)
Observed Maximum Speed (knots)	22.97	36.50	6.95	11	91.67
Published Maximum Speed (knots)	24.70	55.00	5.40	8	66.67
Maximum Speed (optimal reported)	26.75	55.00	5.40	11	91.67
Endurance (minutes)	18.83	30.00	6.00	12	100.00
Payload Capacity (pounds)	1.13	2.00	0.18	7	58.33
Empty Weight (pounds)	2.49	6.47	0.11	8	66.67
MTOW (pounds)	2.68	7.50	0.11	12	100.00
System Cost (USD)	839.84	3421.00	83.97	12	100.00
Communication Range (feet)	3358.44	16368.00	164.04	11	91.67
Video Recording Resolution (p)	2320.00	4000.00	480.00	10 (2 N/A)	88.33
Image Resolution (MP)	11.18	16.00	1.20	10 (2 N/A)	88.83
Applications Supported	3.42	4.00	2.00	12	100.00
Number of Critical Specifications Present	6.17	7.00	5.00	12	100.00

The maximum speed was subcategorized into *observed* (i.e., value captured and recorded during testing), *published*, and *optimal reported*. *Optimal reported maximum speed* represents the greater of the two reported speed values, *observed* and *published*, and was used to support scoring calculation. The published or derived values for all other quantitative measures are also identified in Table 5 and were used in subsequent evaluative scoring and ranking calculations. Through the course of the literature review it was observed that published maximum speed, empty weight, and payload capacity, three critical parameters required for acquisition and operational analysis, had the lowest reporting rates (*58.33 - 66.67%*; Table 5). The reported *n* also included two sUAS that did not include camera sensors or the ability to directly integrate such sensors, resulting in samples for two measures being labelled as “not applicable” (N/A; *video recording resolution* and *image resolution*).

Table 6 contains the results of the qualitative assessment, including the mean, maximum, and minimum ratings, *n*, and the *N Reported* for each measure.

Table 6: Qualitative data results

Measure	Mean (%)	Maximum (%)	Minimum (%)	n	N Reported (%)
Construction Quality	79.75	97.00	52.86	12 (76 reviews)	100.00
Operational Ease	71.20	97.00	34.00	12 (74 reviews)	100.00
Accuracy and Availability of Metrics	84.78	96.88	68.57	12 (76 reviews)	100.00
User Support	75.32	95.63	43.33	12 (76 reviews)	100.00

The subjective assessments used to calculate these ratings were made by the researchers who directly participated in the operational testing; inspecting, operating, and observing the individual flights. Between 74 and 76 ratings were made for each measure. The minimum assessment score provided for a system, was 34.00% (*operational ease*), while the maximum was 97.00% (both *construction quality* and *operational ease*).

Table 7 contains the results of the final evaluation scoring calculations, ordered alphabetically with scores and subsequent ranking identified for each system.

Table 7: sUAS evaluation scoring results

sUAS	Novice Suitability score (%; rank)	Total System Performance score (%; rank)	Cost-effectiveness score (ratio; rank)
3D Robotics Solo	80.27 (5)	81.29 (1)	16.75:1 (11)
DJI Inspire 1	77.79 (7)	81.15 (2)	42.16:1 (12)
DJI Phantom 3 (Standard)	86.19 (3)	76.08 (3)	10.21:1 (7)
Dromida Kodo	52.63 (12)	40.90 (12)	2.05:1 (2)
Dromida Vista	65.94 (9)	50.99 (11)	2.04:1 (1)
Elanview Cicada	65.65 (10)	54.99 (9)	7.09:1 (5)
Helimax Form500	67.41 (8)	63.81 (8)	5.69:1 (4)
Hubsan X4 Pro	82.61 (4)	74.78 (5)	11.77:1 (9)
Parrot Bebop 2	87.95 (1)	75.40 (6)	11.34:1 (8)
Syma X8C Venture	63.28 (11)	53.06 (10)	2.62:1 (3)
Xiro XPlorer G	78.36 (6)	64.81 (7)	9.47:1 (6)
Yuneec Typhoon 4K	86.24 (2)	75.32 (4)	14.60:1 (10)

The *Novice Suitability* scoring ranged from a minimum of 52.63% (Dromida Kodo; 12th of 12) to a maximum of 87.95% (Parrot Bebop 2; 1st of 12), with a mean score of 74.53%. The *Total System Performance* scoring ranged from a minimum of 40.90% (Dromida Kodo; 12th of 12) to a maximum of 81.29% (3D Robotics Solo; 1st of 12), with a mean of 65.97%. The *Cost-effectiveness* scoring ranged from a minimum of 42.16:1 (DJI Inspire 1; 12th of 12) to a maximum of 2.04:1 (Dromida Vista; 1st of 12), with a mean of 11.32:1.

IV. Discussion

UAS consumers are expected to enter this industry from a broad distribution of ages, vocations, and interests. Remote pilots are anticipated to range from those with discerning interests to individuals with potential commercial venture engagement, participating with or without a baseline of knowledge from which to select the best system for their particular uses. By performing and publishing the results of this research, the team was able to identify, locate, obtain, test and evaluate a broad selection of sUAS systems to establish such a baseline for consumer comparison and consideration.

4.1 Research Observations

The level of incorporation or provision for camera sensors, as well as flight control and navigation augmentation, affect the final pricing and creates a potential for future sub-categorization of sUAS. For example, systems could be further divided into five sub-categories regarding camera/sensor incorporation: (1) no camera/sensor provision, (2) integrated camera/sensor without gimbal/stabilization, (3) integrated camera/sensor with gimbal/stabilization (4) provision for third-party camera/sensor without gimbal/stabilization, and (5) provision for third-party camera (sensor) with gimbal or image stabilization. Two additional categories could be derived based on availability and incorporation of navigation augmentation: (1) without global positioning system (GPS), (2) with GPS. However, a more detailed examination also revealed finer nuances, such as the incorporation of support sensors (e.g., RADAR/SONAR altimeter and optical tracker) for flight and navigation augmentation.

A few less obvious differences that were observed in the testing included the system-specific flight control logic that was applied for flight maneuver aspects, such as inertia compensation and drift, descend control, and ground effect handling. For example, there was a notable difference in the distances that systems continued to drift from a rapid maneuver, after the control input was released; one system in the test surprisingly incorporated a control logic that actively returned the platform to the point at which the control input was relinquished. Similarly, higher end systems in the test actively appeared to restrict too rapid descent to prevent “settling with power” (i.e., vortex ring state), a condition in which the rotor re-ingests its own downwash [33], while other systems seemed to have no provision against this possibly catastrophic condition. One system was particularly prone to feedback in ground effect (i.e., observed as bounciness during manual landings), while others had less of an issue or provided landing augmentation (e.g., automatic landing). It also appeared that some of the systems used angle of attack (AoA) to limit airspeed (e.g., a maximum 20 degree angle), while some measured GPS-derived ground speed. This caused a significant performance difference between upwind and downwind speeds when operating in windy conditions.

The lack of standardization was further observed in the provided operational guidance and documentation, including autopilot functionality. For example, in home mode, certain systems seemed to return to the controller position at the time of either start up or home mode activation, while other systems homed to their own lift-off point. It is unclear how published numbers are obtained, whether through calculation, testing and observation, or a combination of methods. Therefore, further research with focus on some of the aspects observed, but not quantified in this study, is recommended for the future.

4.2 Research Challenges

As with any research for an emerging industry, compiling a broad document that could deliver a sufficient cross section of products would be a challenge. The volume of available sUAS available meant that an accurate and representative sample of systems required identification and incorporation. Testing every system in a particular set of parameters would be difficult, as system upgrades and new products emerge nearly weekly. Airspace limitations and certifications also proved a challenge as the study was designed and implemented before the passage of the FAA's release of Part 107. Flight operation certification was obtained in Nevada through integration of the team with NIAS, which allowed for a timely test and evaluation period to support project completion and compliment of the research timeline. Testing was able to occur, as needed, through acquisition of both indoor and outdoor facilities in east central Florida and under the NIAS public COA. The indoor facilities were located at the ERAU-Daytona Beach field house, a large enclosed structure used for athletics and public presentations. Simultaneously, an outdoor area was secured for testing in Samsula, Florida. Operational system testing occurred over a two-day period, supported with three days of preparatory work including systems setup and initial indoor operational testing, logistical operations, facilities inspection, and communication organization.

4.3 Limitations of the Study

The team consisted of individuals broadly distributed geographically, including students, researchers, and faculty from several different aviation and modeling disciplines. Most evaluators were both fixed and/or rotary wing pilots certified in the military and civil industry, but relatively new to the sUAS industry. This background may have been limited in traditional approaches; however, this is likely a potential strength in this study as the aeronautical knowledge and experience supported critical review and the establishment and maintenance of safety. The total available budget, in terms of time and finances, also presented limitations on what could be accomplished, given the intent of the study. Finances to cover acquisition of sUAS, materials, and tools, as well as travel, lodging, and on-site expenses of participants were supported through a donation-based crowdfunding campaign, manufacturer system donations, and university investment.

4.4 Return on Investment

Timeliness of a critical and thorough review by an unbiased team helped to produce a guide, based on a clear and defined set of criteria relating to critical aviation concepts and safety. The produced guide is broad enough to support market entry for recreational and commercial interests, for novice to experienced users. Most importantly, the guide, while selective on systems reviewed, still offers information that can assist the uninformed to produce an assessment of their own, indirectly. By using the same or similar evaluation criteria and process, potential users can apply the principles and method to systems of personal or organization interest. Experience from this test and evaluation project also served to expand and contribute toward the team's operational experience, enabling further research and sUAS application efforts.

4.5 Suggestion for Future Research

This study provided a first opportunity to develop and test a methodology that supports quantification and evaluation of a selection of diverse sUAS criteria. At the heart of the taken approach was the identification, selection, weighing, and quantifying of criteria considered essential for a selected user group (i.e., novice sUAS consumer) to provide acquisition and operation recommendations. The study, therefore, presents a systematic approach to a task-specific suitability analysis of sUAS supported by a combination of objectively obtained data and subjectively assessed operational aspects together with the statistical means to combine and evaluate. A similar methodology could be applied in the future for other specific UAS evaluations. The team acknowledges the inherent limitation of the approach and its resultant recommendations to a very specific set of pre-selected criteria, which is a direct consequence of the narrowly defined focus on one specific audience with limited applications (e.g., training, aerial filming, research, and recreation). Therefore, additional research utilizing a similar methodology for other sUAS applications will have to focus first on defining objectives in a similarly targeted fashion, which highlights that the results of one such specific, application-oriented study cannot be translated uncritically to other applications without a thorough re-evaluation of selected criteria, underlining the need for further research efforts independently conducted for each specific application. This first look at this challenge merely provided a general methodology and some lessons learned for the realization of such research.

Based on the specifics of a selected application, further research may concentrate on criteria centered around (1) sensor integration and performance; (2) operator augmentation and platform automation and autonomy; (3) design of commercial standardized sUAS controller units and operator flight inputs (for industry-wide implementation); (4) sUAS battery development and design for (increasing flight endurance from optimal range of 30 minutes to several hours to enhance sUAS utility for applied applications); (5) smart device simplification methodologies to enhance novice operator's short and long-term experience building and integration; (6) system support for planning and data gathering, storage, and evaluation; or (7) other task specific platform requirements (e.g., modularity and/or interchangeability of payload). Such research with different application in mind may also need to modify the weight assigned to certain criteria as tested in this study. For example, cost or endurance may be assigned a higher priority depending on the intended task. With this further research into other applications (e.g., precision agriculture, public safety, mapping, surveying, and inspection), the additional incorporation of different platform options (fixed-wing, vertical takeoff and landing, hybrid, and internal combustion), sizes, and supporting elements and tools (payloads, controls, training and operational software; and maintenance/repair equipment) into the evaluation is also recommended. In addition, the development of standard performance data capture and reporting from manufacturers would also be beneficial to the sUAS community to provide clear indication of system capabilities and limitations and support subsequent planning, suitability, and safety evaluation.

V. Conclusion

The sUAS industry is unquestionably advancing at an exponential rate and the research team realized that to keep pace with the multiple innovations, changes, and safety concerns, all sUAS stakeholders will need to work together on a platform of common goals and objectives and present a unified front in FAA collaboration. The development and pursuit of this research led to the creation of consumer resources (i.e., *sUAS Consumer Guide* and *Operational Test Plan*) to be widely distributed among the sUAS community, as well as a method to evaluate the capabilities, performance, and qualities of systems. Through further investigation, refinement, and coverage, the value and usability of such evaluations can be expected to help promote thorough consideration of available options, for use in accordance with regulatory requirements. The research findings and observations can also be used to highlight positive attributes and deficits of sUAS design worthy of continued developmental inquiry. It is recommended that future sUAS evaluative research include comparison of common platform types; suitability towards growing applications; and supporting elements and tools. In support of such recommendations, the ERAU team plans to develop and launch a dedicated web resource to host the original results, in addition to new findings and pursuits associated with sUAS evaluation. As active stakeholders in the shared aviation community, it will be essential to share such resources with the public, while also striving to foster collaborative technological advancement to achieve continued success in maintaining safety, efficiency, and effectiveness of global sUAS application and operation.

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VII. Notation

AC	Advisory circular
AoA	Angle of attack (degrees)
COA	Certificate of waiver or authorization
COTS	Commercially-off-the-shelf
FAA	Federal Aviation Administration
ERAU	Embry-Riddle Aeronautical University
GPS	Global Positioning System
HD	High definition
MP	Megapixels
MSL	Mean sea level (feet)
MTOW	Maximum gross takeoff weight (pounds)
n	Number of sample
N	Sample population size
N Reported	Percentage of total number of samples reported
N/A	Not applicable
NAS	National Airspace System
NIAS	Nevada Institute for Autonomous Systems
p	Vertical pixel resolution
SM	Statute mile
SRA	Safety risk analysis
SRM	Safety risk management
sUAS	Small unmanned aircraft system
UAS	Unmanned aircraft system
USD	United States dollar ($)

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