Development of a Process to Define Unmanned Aircraft Systems Handling Qualities

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Unmanned Aircraft Systems (UAS) are no longer coming, they are here, and operators from first responders to package delivery are demanding access to the National Airspace System (NAS) for a wide variety of missions. This includes a proliferation of small UAS or sUAS that will operate beyond line of sight at altitudes of 500 ft and below. A myriad of issues continues to slow the development of verification, validation, and certification methods that will enable a safe introduction of UAS to the NAS. These issues include the lack of both a consensus on UAS categorization process and quantitative certification requirements including the definition of handling qualities. Because of the wide variety of UAS types (fixed wing, rotary wing from traditional helicopters to multi-rotor configurations, ducted fans, airships, etc.) and vehicle sizes, from micro vehicles to the Global Hawk with a wing span similar to that of a Boeing 737, there cannot be a one-size-fits-all set of requirements. To address these issues, a team led by Systems Technology Inc. is developing a process that will guide UAS stakeholders through a systematic handling qualities evaluation process. This work builds on the existing, highly successful, military rotorcraft handling qualities specification that features a mission-oriented approach. In the proposed process, the vehicle is first identified by a weight-based classification and then the associated vehicle missions or use cases are considered. These missions have specific tasks that dictate the criteria and demonstration maneuvers necessary to evaluate handling qualities. An assessment of both modeled responses and flight test data can then be conducted to examine the predicted versus actual handling qualities. A mismatch points to the need for refined models as flight is the ultimate check of handling qualities.

I. Introduction

“...” airplane crash in the middle of a Capitol Hill hearing on drones,” the Washington Post headline reads in a January 21, 2015 on-line article. Only in passing does the article mention that NASA and FAA officials also testified in front of the House Science, Space and Technology Committee, and there is no description of the content of this testimony in the article. Even thought this “crash” was a non-event, this article does reflect the public skepticism regarding UAS integration and use in the NAS.

Other recent government reports and media articles have highlighted more issues. “FAA Faces Significant Barriers to Safely Integrate Unmanned Aircraft Systems into the National Airspace System.” This title is taken from a report generated by the FAA Office of Inspector General that was released on June 24, 2014. The FAA Modernization and Reform Act of 2012 mandated a goal of safe integration of unmanned aircraft systems (UAS)
into the NAS by 30 September 2015. The Inspector General report, however, identified “significant technological, regulatory, and management barriers” that in the end prevented the FAA from meeting this deadline. Of the many shortcomings indicated in the report, two related areas were a lack of certification requirements and an identification of safety risks. A series of high profile articles from the Washington Post in June 2014 exposed to the general public the high number of military drone crashes around the world and the growing number of crashes here in the US. Many of these crashes resulted from aircraft departures from controlled flight that often took the operators by surprise. Below are recorded comments from two operators that appeared in the June 23, 2014 Washington Post article by Whitlock3:

“Drone just pitched up. Drone’s pitching over. Drone is uh, crashed and destructed, at uh, the end of the runway.”

“This thing’s kind of climbing like a pig. Climb, you pig... Boy, this is going to be tight... Okay, interesting. We are falling out of the sky.”

Piloted fixed wing and rotary wing aircraft must demonstrate appropriate handling qualities through a well-defined certification process before access to the NAS is granted. No such process or proven requirements yet exist for UAS. Decades of research with dedicated variable stability aircraft were undertaken to create the databases necessary to define handling qualities requirements. For UAS that range in size from a hand-launched micro air vehicle to the Global Hawk with a wingspan akin to a B-737, no such database exists. In fact, it is difficult to find consensus for what “handling qualities” of a UAS means. Designing flight control systems to meet specified handling qualities, define the safe operation envelope, and regulate an aircraft’s response to violation of the envelope and departure from controlled flight requires data. Such data are sparse for UAS, especially for the flight regimes with nonlinear and ill-behaved vehicle dynamics. These are well-recognized issues, but until recently, no focused research efforts had been funded to define UAS handling qualities. Instead, piloted aircraft requirements, which may or, more likely, may not be appropriate, are often proposed. Even though the FAA has a defined rule set for visual line-of-sight (VLOS) and has been granting more commercial UAS exemptions, the end result is that validation, verification, and certification of UAS systems including the definition of UAS handling qualities remain elusive.

To define UAS handling qualities, there must first be an effective classification scheme. Unfortunately, this goal also remains elusive, despite past and ongoing efforts. The Navy has been particularly concerned with the classification of UAS as part of a larger goal to define quantitative requirements. The Navy approach thus far has been to base classification on the fixed wing flying qualities specifications for piloted aircraft, based on aircraft size and weight. What’s missing from this approach is a consideration of airspeed, a critical factor with regards to assessing safety. Cotting, as part of his doctoral dissertation, proposed an approach that classifies by Reynolds number, Mach number, and weight. A more recent NASA-funded study led by Embry-Riddle Aeronautical University used an expert system approach to map UAS characteristics with operational requirements to derive their classification scheme. Based on this approach, the top three system parameters were maximum kinetic energy, weight, and wingspan. Given a mission-oriented approach as addressed later in this paper, UAS classification can be simplified as the mission addresses many of these considerations.

All of the issues discussed thus far add up to one primary concern – airworthiness of the UAS. That is, the UAS must demonstrate through an approved verification, validation, and certification process an equivalent level of safety to other aircraft operating in the NAS. NATO has been evolving airworthiness requirements for UAS via its STANAG 4671, “UAV Systems Airworthiness Requirements (USAR) for North Atlantic Treaty Organization (NATO) Military UAV Systems.” While there is still a lack of supporting data to quantify many of the requirements and the emphasis is on military operations, it does provide a roadmap for civilian certification in many ways. Foremost, it defines the broad ranges of airworthiness disciplines that must be addressed as part of the certification process including flight, structures, design and construction, powerplant, equipment, operating limitations and information, command and control data link, and control station. It is beyond the scope of this paper to address all of these important areas. Instead, the focus is on defining UAS handling qualities.

There is a wealth of literature available regarding the development and application of fixed wing flying and handling qualities metrics and criteria. There has been a tendency, historically, to use the terms “flying qualities” and “handling qualities” interchangeably. For the engineering community, there is often no recognized difference between these phrases. To some, however, the terms have begun to take on different meanings, and this difference has been reflected, where possible, in this work. The terms are interpreted as follows. “Flying qualities” is taken to mean those analytical and empirical parameters or criteria that can be measured for a given airplane. All such parameters or criteria can be related to the demands the pilot places on the airplane to achieve desired performance. That is, they are open-loop metrics describing pilot-in-the-loop operations.
In contrast, “handling qualities” is meant to describe operations while the pilot is actively in the loop. This includes the definition put forth by Cooper and Harper10: “Those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role.” For UAS, consideration is also given to the ability of the autonomous system to perform the task.

In this context, the “flying qualities” criteria are open-loop measures by which one attempts to quantify the “handling qualities” of the airplane. The most prominent criteria have been included in several incarnations of the military specifications and design standards, including the most recent release of MIL-STD-1797B Flying Qualities of Piloted Aircraft11, while the rotorcraft criteria can be found in ADS-33E-PRF Handling Qualities Requirements for Military Rotorcraft12. A more detailed look at the evolution of aircraft flying qualities can be found elsewhere13.

For military rotorcraft, handling qualities are specified using a highly successful mission-oriented approach. The foundation of the mission-oriented approach is that requirements are based on realistic mission task elements or MTEs, not Flight Phases. The goal has been to tie specific flight test demonstration maneuvers to these MTEs. Ultimately, a truly mission-oriented specification will have all quantitative requirements tied directly to realistic MTEs, and for every MTE, there will be a corresponding demonstration maneuver, as is for the most part done with the rotorcraft design standard. The MTE will be what is expected of the aircraft; the demonstration maneuver will be an explicit way of testing suitability for performing the corresponding MTE. This is perhaps the most significant “mission-oriented” concept. In a sense, this is what the FARs and the Flight Test Guide do for the FAA; however, this approach is applicable to the traditional aircraft response types, else special conditions must be defined.

A mission-oriented approach provides for the possibility of different dynamic response characteristics or response-types. One shortcoming of several of the requirements of MIL-STD-1797B is that they are not applicable to all response-types. As mentioned above, a further significant feature of the mission-oriented approach is the inclusion of demonstration maneuvers as an integral part of the standard as the quantitative requirements defined by predictive criteria are not comprehensive. Meeting these requirements does not guarantee desirable handling qualities or mission performance. Conversely, failing one or more of the requirements is not necessarily a guarantee of less than desirable handling qualities (although it is highly probable). For this reason, qualitative flight test evaluations by experienced test pilots are the fundamental element of the FAA certification process regarding commercial transport flying qualities. For UAS operations, a process in which system performance is quantified via flight evaluations will be an essential component to defining UAS handling qualities. This paper outlines a mission-oriented process — where the vehicle is first identified by a weight-based classification and then the associated mission cases— for defining UAS handling qualities. The process was developed under a Phase I Small Business Innovation Research program conducted for NASA Langley Research Center.

II. The Mission-Oriented Approach

A. Old School – Sorting by Class and Flight Phase

For decades the military fixed wing flying qualities specifications (MIL-F-8785) and standards (MIL-STD-1797) have featured requirements for piloted airplanes that have been defined in terms of specific classifiers – size, weight, and flight phase. The public release of MIL-STD-1797, Version A, defines four fixed wing air vehicle classes as follows:

- Class I: Small, light air vehicles, such as light utility, primary trainer, or light observation.
- Class II: Medium weight, low-to-medium maneuverability air vehicles such as heavy utility/search and rescue; light or medium transport/cargo/tanker; early warning/electronic countermeasures/airborne command, control, or communications relay; antisubmarine; assault transport; reconnaissance; tactical bomber; heavy attack; or trainer for Class II.
- Class III: Large, heavy, low-to-medium maneuverability air vehicles, such as heavy transport/cargo/tanker; heavy bomber; patrol/early warning/electronic countermeasures/airborne command, control, or communications relay; or trainer for Class III.
- Class IV: High-maneuverability air vehicles, such as fighter/interceptor; attack; tactical reconnaissance; observation; or trainer for Class IV.

Given an identified air vehicle class, requirements are further distilled by Flight Phase. MIL-STD-1797A defines three Flight Phases:

- Category A: Those nonterminal Flight Phases that require rapid maneuvering, precision tracking, or precise flight-path control. Examples include air-to-air combat, reconnaissance, terrain following, in-flight refueling (receiver), and close formation flying.
• Category B: Those nonterminal Flight Phases that are normally accomplished using gradual maneuvers and without precision tracking, although accurate flight-path control may be required. Examples include climb, cruise, loiter, in-flight refueling (tanker), and aerial delivery.

• Category C: Terminal Flight Phases are normally accomplished using gradual maneuvers and usually require accurate flight-path control. Examples include takeoff, power approach, landing, carrier approach, carrier landing, and ground handling.

On the surface, this appears to be a “tortoise and hare” approach to requirements. That is, the big and slow tortoise will naturally have different requirements from the small and fast hare. Is this always the case? Consider the AC-130 gunship and the C-130J transport, both considered Class III aircraft. While the airframes are in many ways the same, their missions could not be more different. Does the AC-130’s ground attack mission have more in common with the A-10, a much smaller and lighter Class IV aircraft? If the answer to this question is “yes,” then should not the handling qualities requirements for the AC-130 be more akin to the A-10? If the answer is again “yes,” then an approach to defining handling qualities based on mission can be more appropriate than an approach based on Class or Flight Phase. This may be especially true for UAS where the number of potential classes and flight phases is expansive. When a vehicle is asked to perform disparate missions, a mission-based approach, in contrast to class/flight phase, will serve as a diagnostic tool with direct implications for design requirements.

B. Using Mission as the Classifier

For handling qualities flight test evaluations, it is desirable to categorize segments of the missions into handling qualities evaluation tasks. The ability of the aircraft to accomplish these tasks is predicted according to the appropriate criteria. Parameters for these requirements are generated first analytically, then via simulation, and finally via flight test. It is not practical, or necessary, to derive a separate set of criteria for every defined task. Instead, the tasks are grouped in terms of the criteria boundaries that apply to them. The task definitions include specific desired and adequate performance requirements to facilitate evaluation test pilot use of the Cooper-Harper handling qualities rating scale. In a mission-oriented approach to aircraft handling qualities requirements are based on realistic MTEs, not the general Flight Phases identified above that define the current and long-standing approach to piloted fixed wing aircraft flying qualities. An MTE therefore defines a specific flight test demonstration maneuver.

Ultimately, a truly mission-oriented UAS specification will have all quantitative requirements tied directly to realistic MTEs. The associated MTE requirement will be what is expected of the UAS; the MTE itself will be an explicit method of test to evaluate handling qualities in piloted simulation and flight test. This is perhaps the most significant “mission-oriented” concept and, as such, led to the research effort reported in Reference 9. This fixed wing research was based on the mission-oriented approach to handling qualities that was successfully established for military rotorcraft via ADS-33.

In the mission-oriented approach, references to Class are removed. A number of the requirements in MIL-STD-1797A have different values depending upon aircraft size, defined in terms of four Classes of aircraft, particularly the modal requirements that were defined in MIL-F-8785 and have remained through the current version of the fixed wing standard. This division is arbitrary, and is sometimes irrelevant. For example, if a particular mission requires a high level of aggressiveness and precision, it should not matter if the airplane proposed for that mission is small or large. Only the mission requirements should set handling qualities. It is recognized that, in some cases, this may lead to unreasonable demands on very large airplanes. Returning to the previous transport example, if the AC-130 is required to perform ground attack, then the Level 1 roll performance limits stated for Class IV fighters may be unachievable without the use of extremely fast actuators and the possible introduction of very high lateral accelerations at the pilot’s station. In this case, it should be obvious that either (1) a new MTE, such as transport ground attack, with relaxed mission demands needs to be defined, or (2) it is simply not possible to build a Level 1 transport for the ground attack task. Because the AC-130 has been highly successful in the ground attack mission, the former is the more likely scenario. The mission-oriented classifier can therefore serve as a way to identify unrealistic mission requirements for some aircraft.

A mission-oriented approach provides for the possibility of different dynamic response characteristics or flight control system response-types. One shortcoming of several of the requirements of MIL-STD-1797A is that they are not applicable to all response-types. For example, aircraft with an attitude response-type such as pitch attitude command/attitude hold dynamics should not be evaluated using the control anticipation parameter (CAP) criteria for short-term response. The number of different response types possible for fixed wing airplanes is not extensive, so this amounts, in essence, to simply amplifying the guidance to the user. For UAS that can feature many unique response types and levels of autonomy, requirements that are invariant to these elements of the design are needed.
Finally, one of the most significant features of the mission-oriented approach is the inclusion of MTEs as an integral part of the standard. This was done for rotorcraft in ADS-33 and in an initial fixed wing catalog of maneuvers\textsuperscript{15}, but these maneuvers have not yet been incorporated into the fixed wing standard. The quantitative requirements of MIL-STD-1797A – or any other requirements – are not now, and can never hope to be, completely comprehensive. Therefore, qualitative flight test evaluations by trained evaluators that are familiar with the handling qualities rating process as established by Cooper and Harper\textsuperscript{10} should be made an integral part of the handling qualities assessment process. For the evaluation of UAS handling qualities it is recognized that modifications to the rating process including alternate rating scale versions will be required, based on the role of the pilot/operator.

The addition of MTEs allows for two separate methods for assessing the Levels of UAS handling qualities:

- **Predicted Levels based on handling qualities parameters.** Here, comparisons are made with quantitative boundaries of handling qualities parameters. When establishing compliance, the parameters of the UAS are determined and compared with the boundaries appropriate to the MTE requirements. These criteria are inherently single-axis. A Level 1 UAS must meet the Level 1 standards for all of the criteria. The quantitative criteria are based on previous experiments and analyses, and hence result in predicted Levels of handling qualities. When using a given requirement, users should have a good understanding of the theory behind a particular requirement and the supporting data that were used to define the quantitative requirements.

- **Assessed Levels based on flight test maneuvers.** The second method of establishing Levels is to perform a set of well-defined flight test maneuvers (i.e., the defined MTEs) using a team of at least three test pilot/operator evaluators. These evaluators assign Cooper-Harper Handling Qualities Ratings\textsuperscript{10} or HQRs to the aircraft for each maneuver. The collective HQR determines the Level for each maneuver and a Level 1 aircraft must be rated Level 1 for all of the maneuvers designated as appropriate to its operational requirements. As mentioned above, revisions to this rating process will be needed for UAS evaluations to include autonomous operations, for example. The flight test maneuvers may be either single-axis or multi-axis by design, though it may be appropriate to evaluate the aircraft one axis at a time first before moving to multi-axis evaluations. Compliance with the flight test maneuvers is based on piloted evaluations, and therefore results in assigned Levels of handling qualities. These pilot/operator evaluations will provide the ultimate check of UAS handling qualities for remotely piloted modes. Quantitative assessments of mission performance will also be important, especially for autonomous modes of operation, which will soon dominate UAS operations.

C. **Mission Task Elements**

It is desirable to categorize segments of the mission into specific tasks. The ability of the aircraft to accomplish these tasks is measured according to the appropriate requirements. The mission tasks in the mission-oriented specification are more formally defined as “Mission Task Elements” or MTEs. It is intended that the MTEs be specified in detail, including performance requirements. Furthermore, flight phase categories are defined in terms of the level of precision and aggressiveness required of the UAS. For human remote operations, consideration of compensation and workload as revealed by the response to the required precision and aggressiveness are part of the rating process. For autonomous operations, precision and aggressiveness requirements will expose the robustness of the controller. Four MTE categories are defined as follows:

1. **Non-Precision, Non-Aggressive**

   Non-precision tasks that require only a moderate amount of remote pilot or autonomous system control fall in this category. Example tasks from this category include:
   - Heading, altitude, and speed changes for general maneuvering or to enhance on-board sensor performance;
   - Non-precision station keeping (e.g., weather monitoring, wildfire monitoring, internet access provider, etc.).

2. **Non-Precision, Aggressive**

   This category is intended to include the large amplitude maneuvering MTEs that emphasize control power over crisp dynamics. It is true, however, that a reasonably good dynamic response is inherently necessary to effectively utilize a large amount of control authority, i.e., to stop and start the large amplitude maneuvers with some precision (recall the old control power vs. damping plots). The moderate- and large-amplitude maneuvering requirements will be of primary interest for these MTEs. This category will invoke some of the existing control power criteria, as well as other agility criteria. Example tasks from this category include:
• Ground-based or air-based obstacle avoidance in non-dense environments; and
• Gross acquisition of air or ground targets.

3. Precision, Non-Aggressive

This category includes tasks where considerable precision is required, but without the aggressive control activity. The dynamic response requirements for these tasks are expected to be less stringent than for Precision, Aggressive, but significantly greater than for Non-Precision, Non-Aggressive. Example tasks from this category include:

• Precision landings;
• Precision path following at altitude (e.g., border patrol, highway/roadway/railway monitoring, etc.);
• Precision station keeping;
• Precision hover;
• Precise pitch attitude and bank angle captures; and
• Final approach and landing for package delivery.

4. Precision, Aggressive

This category includes precision tasks, where an extremely crisp and predictable response to control inputs is required. The results of not achieving the required precision are usually significant in terms of accomplishing the mission or safety of flight. Example tasks in this category include:

• Air-to-air and air-to-ground fine tracking;
• Low altitude precision path following (e.g., crop dusting/monitoring, pipeline scanning, etc.); and
• Ground-based or air-based obstacle avoidance in dense environments, e.g., urban, densely populated.

5. MTE Categories and Candidate UAS Handling Qualities Requirements

The intent of the MTE categories is that the requirements in a given category are sufficiently similar so that a single criterion boundary will apply. For example, the Bandwidth criterion should have a form similar to that shown in Figure 1. As described elsewhere in this paper, data are required to properly define these boundaries for UAS applications.

Figure 1: Relationship between MTE categories and specification boundaries for Aircraft Bandwidth criterion as defined by phase delay (\(\tau_p\), sec) versus bandwidth frequency (\(\omega_B\), rad/s).

D. Classification

1. Background

Building on the material in the Introduction, the common denominator in all of the past classification approaches is size, weight, and airspeed. Clearly size and weight are tied together, although examples of very large but lightweight and very small but dense UAS examples can be identified. Neglecting the fringe examples, however, a combined weight (or mass) and speed classifier is attractive. Such an approach can be applied to vehicles defined as sUAS or small UAS that are designed to fly at relatively low speeds and low altitudes (i.e., < 500 ft) and weigh less
than 55 pounds and UAS that are designed to operate at higher altitudes assigned to the NAS and weigh more than 55 pounds though they currently typically operate in restricted airspace. A small sampling of the wide variety of UAS is shown in Figure 2.

Figure 2: Example UAS.

2. **Consideration of Class and the Pilot/Operator**
Throughout 2016, the FAA has been moving more rapidly to develop rulemaking for UAS. The focus thus far has been on those small UAS that weigh 55 pounds or less and are designed to operate primarily at altitudes below
500 feet. Rules for operating vehicles in this class were released on June 21, 2016\textsuperscript{16}. Operational limitations include the following:

- Visual line-of-sight operations only;
- Daylight-only operations;
- Maximum groundspeed of 100 mph (87 knots) and a maximum altitude of 400 feet AGL; and
- Operator must hold or be under the direct supervision of someone who holds a remote pilot certificate.

Above this UAS class, the sizes and weights of current vehicles including those exemplified in Figure 2 are significantly larger and significantly heavier. Furthermore, these vehicles are designed to operate at much higher altitudes and much greater speeds than the under 55 pound vehicles. While the majority of these vehicles only operate in restricted airspace, the FAA has recently awarded the General Atomics Aeronautical Systems Predator C Avenger an Experimental Certificate (EC) that enables this vehicle to perform “routine operations” within the NAS. This is the first jet-powered remotely piloted aircraft to receive an FAA EC.

A unique group of UAS vehicles that falls below the under 55 pound weight is the micro UAS. The FAA is currently considering rules for this weight class that is defined as 250 grams (0.55 pounds) or less\textsuperscript{17}. These vehicles are small enough to operate indoors as well as outdoors. With configurations that can vary significantly (e.g., flapping wing designs, vehicles with perching capabilities, etc.) and feature unique dynamic modes, it is beyond the scope of this Phase I project to address these vehicles, but they will be considered in Phase II.

While further weight classifications will be added as work continues, the following weight classifiers based on designations recognized by the FAA and elsewhere will be used herein as a starting point:

- UAS (Weight > 55 pounds);
- sUAS (0.55 < Weight < 55 pounds); and
- uUAS (Weight < 0.55 pounds).

Other classifiers such as speed, type (e.g., fixed wing, rotary wing, ducted fan, etc.) will be captured by vehicle mission as discussed later in this paper.

The role of the pilot is an important factor in defining UAS handling qualities. For a remote pilot that is actively engaged in flying the vehicle, issues such as latency in pilot inceptor to vehicle response may be an important factor and must be reflected in the requirements. On the other hand, an autonomous system can be considered an on-board “pilot” where the impact of the guidance, navigation, and control functions of the software must be considered in the handling qualities assessments. Thus, the role of the pilot/operator will be reflected in the requirements that are linked to a given MTE.

Historically, handling qualities are defined for piloted aircraft. UAS operations may be:

- Remotely Piloted;
- Remote Pilot Assisted (delegated or supervised);
- Fully Autonomous; or
- A combination of the three.

The above correspond with the four levels of autonomy as defined in the DoD Unmanned Systems Integrated Roadmap\textsuperscript{18}. These definitions are repeated below:

- Level 1 – Human Operated: The human operator makes all decisions. The system has no autonomous control of its environment although it may have information-only responses to sensed data.
- Level 2 – Human Delegated: The vehicle can perform many functions independently of human control when delegated to do so (e.g., autopilot functions). This level encompasses automatic controls, engine controls, and other low-level automation that must be activated or deactivated by human input and must act in mutual exclusion of human operation.
- Level 3 – Human Supervised: The system can perform a wide variety of activities when given top-level permissions or direction by a human. Both the human and the system can initiate behaviors based on sensed data, but the system can do so only if within the scope of its currently directed tasks.
- Level 4 – Fully Autonomous: The system receives goals from humans and translates them into tasks to be performed without human interaction. A human could still enter the loop in an emergency or change the goals, although in practice there may be significant time delays before human intervention occurs.

When actively engaged in flying, the pilot provides GNC functions. Autopilots can provide regulation of some of these functions, but they are not autonomous functions, they are regulators. Autonomous functions feature a decision making capability that attempts to replicate or even improve upon piloted operations. If a UAS mission is to, for example, station keep over a given location it does not matter in terms of handling qualities whether it is remotely piloted or autonomous; the mission requirements will be the same.
As introduced herein, a number of classification techniques of varying complexity were considered. Because UAS handling qualities was defined using the mission-oriented approach, a simple classification technique based on weight classifications was selected. Further classifications will come naturally from the MTE selection that will then identify handling qualities requirements or flight test procedures that will be used to predict handling qualities via the analysis path and verify handling qualities via test.

### III. Requirements in a UAS Handling Qualities Specification

#### A. Defining Requirements

1. **Emerging Requirements**

   It was beyond the scope of the initial work to completely define a set of UAS handling qualities requirements, so the objective as described herein was instead to provide structure and processes that can be completed in follow-on work. The team cannot emphasize strongly enough that a key to maturing any UAS handling qualities requirement is flight test data for all three modes of operation – manual (RPA), assisted, and autonomous. It will take a dedicated effort by the UAS community to generate such a database.

   2. **“Requirements” for Requirements**

   As UAS HQ requirements are defined they should meet the following three criteria:

   1. **Validity** – Validity implies that the metrics are associated with properties and characteristics that define the environment of interest. Specifically, in this application, valid metrics will differentiate between desirable, acceptable, and unacceptable handling qualities.

   2. **Selectivity** – Selectivity demands that the metric differentiate sharply between “desirable” systems and those that are merely “acceptable.” This assures that there will be no question at all about selecting between “desirable” and “unacceptable” per se.

   3. **Ready Applicability** – Ready applicability simply requires that the metric be easily and conveniently applied. Its expression in terms of readily available system parameters should be compact; procedures for its analytical evaluation should be convenient; and it should be easily measured in terms of either simulation models and/or empirical operations on the actual airplane and its systems.

3. **The Need for Data**

   A successful set of UAS HQ requirements cannot be established without flight test data. Data are needed for all UAS classes and MTE categories. For example, the fixed wing and rotary wing specifications for handling qualities (i.e., MIL-STD-1797B and AD-33E-PRF, respectively) were built over decades of dedicated flight test with variable stability aircraft, piloted simulation, and analytical studies. Regarding analytical studies, models for a wide variety of UAS are also needed to assess requirements analytically. In the absence of data, requirements established for manned vehicles have been considered and applied. Is this an appropriate approach? How do these requirements apply to sUAS? To answer these questions a process to begin to generate necessary data will be exercised as part of follow-on work.

#### B. Effect of Input Amplitude on Handling Qualities

Military flying qualities requirements in MIL-STD-1797B generally fall into one of two categories: 1) criteria for small-angle, closed-loop control, and 2) criteria for large-angle, open-loop control. Examples of small-angle criteria include Aircraft Bandwidth in pitch, which is concerned with fine tracking or precise attitude control, and roll mode time constant in roll. Examples of large-angle criteria include control force per g in pitch and time to roll through a specified bank angle in roll. There is no specific limitation on the small-angle criteria in the standard, meaning the required response must be maintained throughout at least the Operational Flight Envelope. There is, however, a natural pilot acceptance of lower response bandwidths as maneuver amplitude increases, that is, as the pilot’s concern shifts from precision to aggressiveness.

In the 1980s, a concerted effort was made to identify the region between small-angle and large-angle control. This region was defined by some experts as “agility” – in essence, the ability to rapidly change flight path and control to achieve a new flight condition.

A mission-oriented flying qualities specification must account for all maneuver amplitudes. The region between fine tracking and pure large-amplitude control entails some aspects of control power (for example, how quickly the aircraft rolls) and Aircraft Bandwidth for example, how precisely the pilot can attain the new bank angle).

This distinction between maneuver amplitudes has become even more important with the advent of high-gain, high-state feedback control systems, where maneuvering commands to the control surface effectors might momentarily exceed the capability of those surfaces to keep up. Sudden loss of control, sometimes in the form of pilot-induced oscillations (PIO), is often the result.
The story is no different for UAS; in fact, with the loss of awareness of the remote pilot that the system may be commanding excessive attitude, rates, or accelerations, the possibility for loss of control may be more prevalent. In an autonomous vehicle, system monitors and or envelope limiters must be in place to provide the pilot monitoring function.

The rotorcraft flying qualities specification ADS-33E-PRF deals with maneuver amplitude by specifying three different forms of requirements: Aircraft Bandwidth for small amplitudes, Attitude Quickness for moderate amplitudes, and minimum achievable angular rate or attitude for large amplitudes.

Neither MIL-STD-1797B nor ADS-33E-PRF explicitly defines amplitude of response; with experience gained over the past two decades, it is possible to speculate on what is meant. The following are intended as guidelines only at this time, as the team will focus future efforts to determine if the definitions are appropriate for UAS, and especially if they need to be adjusted for mission or vehicle size.

- **Small Amplitude**: those inputs and responses intended to provide precise control (closed-loop control if remotely piloted), generally corresponding to attitude changes of 10 degrees in pitch, roll, or yaw; and normal accelerations from trim of about 0.2g, lateral or longitudinal accelerations of about 0.1g.
- **Moderate Amplitude**: those inputs and responses intended to produce attitude changes from trim of more than 10 and less than 30 degrees in pitch, roll, or yaw; and normal accelerations from trim of more than 0.2 and less than 0.5g, lateral and longitudinal accelerations of more than 0.1 and less than 0.2g.
- **Large Amplitude**: those inputs and responses intended to produce motions larger than the upper limits defined for moderate amplitude.

C. Time as a Response Metric

Two other ill-defined terms, used in multiple requirements in ADS-33E-PRF, are “short-term” and “mid-term” as delineations for response times. The only definition is hinted at in a couple of requirements that state that mid-term requirements “apply at all frequencies below the bandwidth frequency,” but this is very vague: it is possible for UAS to have a wide range of Aircraft Bandwidth frequencies, meaning “mid-term” is also a variable. If one is going to adopt different requirements for different response time ranges, a more precise definition is needed.

Realistically, it may not be necessary to differentiate explicitly between short- and mid-term; this delineation occurs naturally by using requirements on Aircraft Bandwidth (inherently short-term, whatever the definition) that extend from small to large input amplitudes; and control power for full control inputs, implying “mid-term” response.

IV. The Proposed Process

A. Defining the Process

The proposed process as illustrated in Figure 3 begins with UAS classification. Because of the wide variety of UAS types (fixed wing, rotary wing from traditional helicopters to multi-rotor configurations, ducted fans, airships, etc.) and vehicle size from micro vehicles to the Global Hawk with a wing span like that of a Boeing 737, there cannot be a one-size-fits-all set of requirements.

![Figure 3: The proposed UAS handling qualities assessment process.](image)
Given an appropriate classification, a mission in the form of mission task elements is next considered. Missions may be as varied as the vehicle types. Examples include air-to-air and/or air-to-ground sensor tracking for surveillance, terrain surveying for pipelines or agriculture, entertainment or real estate filming, weather monitoring, package delivery, and wifi access. Missions are then broken down into specific task elements that include those elements that will be a part of any mission (e.g., takeoff and landing) to those that are mission specific (e.g. precision target tracking, high altitude loiter, obstacle avoidance, etc.). These mission task elements are used to identify specific criteria that predict handling qualities analytically and test demonstration maneuvers that verify handling qualities in flight.

B. Exemplifying the Process

1. AirSTAR

To demonstrate the UAS handling qualities process, the NASA GTM model, which is now available for download without restrictions (https://github.com/nasa/GTM_DesignSim), was used. This model was selected because it is defined throughout its flight envelope, it is well documented, and it falls within the under 55 lbs classification. Furthermore, AirSTARS flight test data has been made available for an approach flight condition that was used to compare against the model results\textsuperscript{19}. For the evaluations and examples shown below, only data that were collected in Mode 1 (direct mode control law) were considered. The analysis process is demonstrated using Aircraft Bandwidth as a representative handling qualities metric.

A representative transfer function model of the AirSTAR was extracted from the Simulink-based simulation model. The bare airframe dynamics were identified directly from the included model. Since there was no feedback command, the command path dynamics were noted (system delays and a first order actuator model) and appended to the bare airframe system. Models for the AirSTAR in Mode 1 are shown in Figure 4 with the identified transfer functions\textsuperscript{*}.

2. Aircraft Attitude Bandwidth and Phase Delay

The Aircraft Bandwidth criteria, measured from a frequency response (Bode plot) of attitude to control input (position or force), were developed for the evaluation of handling qualities of highly-augmented airplanes where more conventional criteria could not be easily applied\textsuperscript{20}. These criteria are included in MIL-STD-1797A and formed the basis of the US Army’s rotorcraft airworthiness standard ADS-33E-PRF. The fixed wing requirements for handling qualities levels as published in MIL-STD-1797A have been found to be much too stringent and have been adjusted significantly, especially given the addition of a requirement on pitch rate overshoot. Furthermore, the requirements have also been adapted to the prediction of PIO susceptibility\textsuperscript{21}.

The fundamental theory behind “Aircraft Bandwidth” – which is not the “classic bandwidth” that is used in other control systems applications – is that the principal stability characteristics of the aircraft can be described by the frequency response of angular attitude for control inputs. This is true, at least, for continuous closed-loop control of attitude by the pilot, and when attitude is used as an inner loop to generate changes in load factor or flight path. The concept is that the aircraft should have good inherent stability, whether from basic design or by augmentation with a SAS. The lower this inherent stability, the more stability the pilot must provide to perform required tasks, resulting in increasing workload, degraded flying qualities, and ultimately, PIO.

There are three measures in the criteria that capture the basic pitch attitude characteristics of the aircraft (Figure 5). The first is the “phase margin Bandwidth frequency,” the lowest frequency for which there is a phase margin of 45 degrees. The higher this frequency, the better attitude follows control inputs: if phase margin is 180 degrees, that is, phase angle is zero, then output follows input exactly. At the frequency for 0 degrees phase margin – the “neutral-stability” or 180-degree frequency – attitude is exactly out of phase with inputs. If the phase margin Bandwidth frequency is very low, the pilot must generate lead to improve the overall response of the pilot-plus-aircraft system to perform a task.

The second measure is the “gain margin Bandwidth frequency,” and it is basically the same type of measure, except it determines the change in effective-aircraft dynamics the pilot will encounter if closed-loop gain is increased by a factor of 2 (6 decibels).

The third measure, inappropriately named “Phase Delay,” is really a measure of how rapidly the phase angle of attitude/control inputs degrades at high frequencies. The assumption is that, if the pilot should find it necessary to operate at higher frequencies – which can be done with closed-loop stability only if the pilot generates lead

\textsuperscript{*} The transfer function is represented in standard STI notation: \((s+a) = (a), s^{2}+2\alpha \zeta +\omega^2 = [\zeta, \omega] \)

\textsuperscript{†} Note also that the Bode magnitude has not yet been adjusted to match the flight vehicle.
compensation – a gradually-degrading phase curve is much better than a rapidly-degrading one. Phase delay has been mistakenly equated with pure time delay.

There are aircraft where PIO is unlikely on the basis of the attitude Bandwidth characteristics alone. In some instances, high pitch rate overshoot is a contributor, and limits are placed on the frequency-domain-based metric, ΔG(q) (Figure 6). In others, inadequate flight path control is the culprit, so limits are placed on flight path Bandwidth frequency, ω

\[ \theta = \frac{21.64(0.0487)(2.13)}{0.07315,0.3046} e^{-0.015s} \]

a) Pitch attitude to longitudinal stick position

\[ \phi = \frac{25.04(-0.02412)(0.1758,5.586)}{0.04038 5.927 0.134,6.003} e^{-0.015s} \]

b) Roll attitude to lateral stick position

**Figure 4:** AirSTAR models with the Mode 1 control law.
3. System Identification

As part of the flight evaluations of the AirSTAR, select runs were used to perform system identification maneuvers. These were labeled as Morelli sweeps in the run logs provided and were injected directly at the control surfaces. Since these data covered only the bare airframe dynamics (pitch rate to elevator), the output pitch rate signal was passed through a system that contained the command path features (i.e., identified delays and actuator dynamics) from the Simulink model. Example time histories for the input (elevator command) and the adjusted output (pitch rate), are shown in Figure 7a.

Using the available flight test data and models, several cases were examined: 1) adjusted flight test data; 2) simulation time history data generated with the elevator input from the flight data passed through the simulation model; and 3) the transfer function model. The transfer function model included a gain adjustment to properly match the magnitude responses and account for the un-modeled control input gearing. Simulation results for case 2 are shown in Figure 7b.
4. Process Demonstration

Flight and simulation model pitch rate to longitudinal command frequency responses were generated as shown in Figure 8 where the model transfer function is represented by the solid blue line, the identified flight data is shown as the dashed red line, and the identified simulation model is shown as the dotted black line. As stated earlier, the flight test data was adjusted to include the command path elements. The transfer function model magnitude was adjusted to match flight at the short period frequency, i.e., 6 to 7 rad/s, to set the control gearing not included in the defined transfer function model. The phase response in general matched throughout the considered frequency region. Flight and model results diverge as flight data coherence falls off, particularly at the highest frequencies shown.

Figure 7: Example AirSTAR system identification runs.

Figure 8: Model and identified frequency responses for pitch rate to command ($q/\delta_{\text{elevator}}$).
Aircraft Bandwidth parameters were computed for the three cases; flight, computer simulation, and transfer function model. The pitch attitude frequency response was used to compute the gain and phase bandwidth frequencies, an example of which is shown in Figure 9 for the flight test data. Here, the raw fast Fourier transform results are shown as red circles, while the log-binned results are shown in blue. The binned data are filled for high coherence points and left as open circles when the coherence drops below 0.65. In this example, the Aircraft Bandwidth parameters are all measured in the high coherence region. The related pitch rate overshoot parameters were also computed though for the sake of brevity they are not included herein.

![Figure 9: Identified pitch attitude to command frequency response (θ/θroad).](image)

The parameter values and those computed for the other cases are plotted together in Figure 10a. The bounds indicated are representative of current fixed-wing handling qualities (black lines) and PIO (solid red lines) requirements for piloted aircraft. These transport category requirements for landing are shown in Figure 10b with annotations. One can see that the manned requirements are mismatched with the significantly higher bandwidth frequencies that naturally emerge from the sUAS. Though the parameters remain valid measures, new requirements will need to be established from the emerging UAS flight test databases.

![Figure 10: AirSTAR example Aircraft Bandwidth results.](image)

V. Conclusions

The mission-oriented approach with its emphasis on quantifying vehicle performance via mission task elements was found to be a viable method for defining UAS handling qualities, since proposed requirements can be applied regardless of method of operation (i.e., piloted, pilot monitored, or fully autonomous). Given this assertion, the following conclusions are made from the initial work reported on in this paper:

- Application of the mission-oriented approach allowed for the definition of a much simpler UAS classification method.
• The AirSTAR model and flight test data provided by NASA LaRC represented the type and quality of data that are necessary to effectively predict and verify UAS handling qualities.
• The predicted and flight verified pathways of the mission-oriented process defined herein were successfully exercised using the AirSTAR analytical models and flight test data thereby demonstrating the efficacy of the proposed approach.

The handling qualities, once validated, can serve as valuable feedback to UAS design and re-consideration of mission requirements if important deficiencies are identified.

References