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Flying Qualities Specifications and Design Standards for Unmanned Air Vehicles

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An increasing number of unmanned air vehicle (UAV) systems are being developed for use by the U.S. Navy and Marine Corps. The adequate design and development of UAV platforms is crucial to future fleet operations. Flying qualities standards and criteria are currently deficient for UAVs and rely heavily on manned air vehicle standards and guidance. UAV specific missions, tasking, and payload requirements warrant development of new standards and criteria. Inadequate flying qualities specifications for UAVs may lead to reduced operational effectiveness, high loss rates, increased development cost and delays, and unnecessary design requirements. Typical guidance used in developing UAV platform system specifications for flying qualities has been MIL-F-8785, MIL-HDBK-1797, MIL-HDBK-516, and ADS-33-PRF. These documents, developed as manned specifications, are correlated to pilot comfort and abilities, and have not been updated to address UAV specific needs and requirements. Current UAV specifications do not take into account sensor and payload mission requirements, and changes in basic flying qualities criteria that would allow more flexibility to the UAV designer without compromising airworthiness or mission performance. For example, traditional stall warning devices that ensure safe margin for pilots could be replaced with requirements for sensors and software that recognize and recover from upset conditions when they occur. Modifications to the existing manned flying qualities specifications go well beyond removing requirements for stick force gradients, but delve into the basic stability and control requirements of the airborne system itself. A UAV design should be aided, not hampered, by the more than 100 years of manned aviation history, to reach its full potential for mission performance. This paper briefly assesses the contents of the various fixed wing flying qualities specifications, identifies certain deficiencies with respect to UAVs, and proposes the development of new flying qualities criteria, specifications, and design standards specific to UAV platforms. Additionally, this paper identifies key research areas for the future.

I. Nomenclature

AOA	Angle of Attack
CFD	Computational Fluid Dynamics
DoD	Department of Defense
HQR	Handling Qualities Rating
n_z	Normal Acceleration (body-axis)
NACA	National Advisory Committee on Aeronautics
NAVAIR	Naval Air Systems Command
$\lvert\varphi/\beta\rvert_d$	Dutch Roll mode bank angle to sideslip angle ratio

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PIO	Pilot Induced Oscillation
SAE	Society of Automotive Engineers
SIO	System Induced Oscillation
UAS	Unmanned Air System
UAV	Unmanned Air Vehicle
U.S.	United States of America
USAF	United States Air Force

II. Introduction

Over the past few decades, the number of unmanned air vehicles (UAVs) in use by the U.S. Navy and Marine Corps has increased rapidly. Unfortunately, the aerospace community's understanding of how flying qualities relate to UAVs has not kept pace. Current flying qualities design standards were developed for piloted aircraft and have not been updated to handle UAV unique problems. Due to the differences between ways piloted aircraft and UAVs are designed and operated, certain existing criteria do not apply to UAVs. This can cast doubt on the validity of the specifications and standards as a whole with respect to their applicability for designing UAVs. Flying qualities design specifications and guidance documents are "intended to assure flying qualities that provide adequate mission performance and flight safety regardless of design implementation or flight control system mechanization."[1] Therefore, new UAV specific requirements and guidance need to be developed and the existing specifications and standards need to be updated.

This paper briefly assesses the piloted flying qualities specifications and standards and their shortcomings related to fixed wing UAVs. Research will be focused in two veins: adapting piloted specification to use for UAVs, and developing new criteria derived directly from mission performance requirements. Adapting piloted specification entails research to determine appropriate quantitative design criteria for UAVs, such as Dutch Roll damping or Short Period frequency. Research into new criteria, not based on piloted specifications, will focus on deriving tasks and tolerances from mission needs to tie UAV flying qualities directly to top level system requirements. The approach outlined distinguishes requirements between those important for mission performance and those important for airworthiness. Although NAVAIR needs to address remotely piloted and rotary wing UAV specifications, they will not be discussed in detail here. The purpose is not to solve the problem here, but to raise the awareness and to motivate and direct future research in flying qualities.

A. History of Piloted Flying Qualities Specifications and Standards for Fixed Wing Aircraft

Flying Qualities have always played a large role in the design, development, testing, and operation of piloted aircraft. Satisfactory flying qualities ensure that the pilot is capable of flying the desired mission safely and successfully with the minimum amount of pilot workload associated with given tasks. Many developments have been made over the past century with respect to flying qualities design specifications and standards. A summary timeline of the major documents and revisions is presented in Figure 1. Even before the first specification or standard was created specifying flying qualities, the Wright brothers had spent considerable time flying gliders to understand the nuances of aircraft controllability prior to flying their first powered aircraft.[2] In 1908, the U.S. Army contracted the Wright brothers to manufacture the first military aircraft. Requirement #10 in the Army Corps Specification No. 486, which could be regarded as the first flying qualities requirement, stated: "It should be sufficiently simple in its construction and operation to permit an intelligent man to become proficient in its use in a reasonable length of time."[3] Although this is not an explicit flying qualities requirement, it still points to the source of future flying qualities requirements – the need to adequately control the aircraft to safely perform its mission.

Early stability and control requirements did not provide design guidance to aid aircraft manufactures in developing airplanes with acceptable flying qualities. The National Advisory Committee on Aeronautics (NACA) undertook a research effort in flying qualities beginning in 1936 to provide quantitative design criteria. This first, formal flying qualities research program measured the flying qualities of more than 60 airplanes of all kinds in flight tests and in lab tests with simulated cockpits. Analysis of aircraft designs, flying qualities data, and pilot comments provided the initial basis for flying qualities requirements.[4] Flying qualities research has continued to follow the path set by NACA in the 1930s, even as new criteria have been developed over the years to keep pace with rapid advances in technology. In order to develop criteria that can be used early in the design process, there must be flight tests and/or simulations to correlate pilot ratings to the quantitative requirement. Test results are usually validated by comparing the new proposed requirement to existing aircraft. The validation shows that following the quantitative design requirement leads to an aircraft with which pilots can adequately perform their mission.

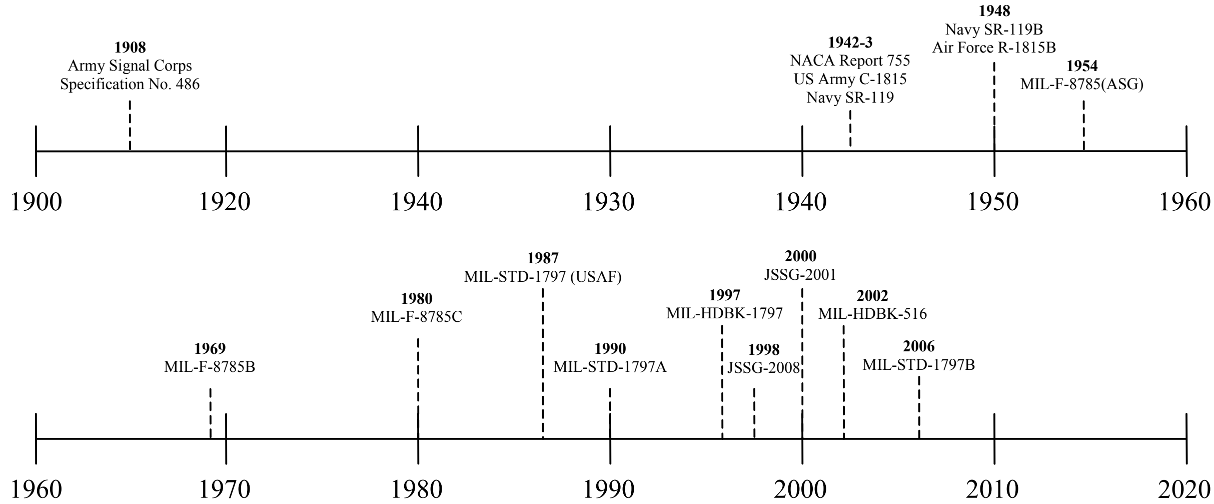

Figure 1: Major Milestones in Fixed-Wing Piloted Flying Qualities Specifications and Standards

Prior to and during World War II, the U.S. military was procuring an increasing number of aircraft which highlighted the need for specific aircraft requirements. These aircraft were designed without an official flying qualities document and as a result the flight characteristics of the aircraft were allowed to vary considerably. Based on the aforementioned 1930s research, NACA issued the first technical flying qualities requirements document for both civil and military aircraft in 1943, "Requirements for Satisfactory Flying Qualities of Airplanes" (NACA Report 755).[5] Also based on the NACA research, the U.S. Army and Navy issued similar specification documents including flight test procedures to verify requirement compliance – C-1815[6] and SR-119,[7] respectively. Shortly after the conclusion of World War II, the first multi-service flying qualities document was issued in 1954 – MIL-F-8785.[8]

The 1969 revision, MIL-F-8785B[9] was the beginning of modern flying qualities documents in that, for the first time, detailed desired aircraft modal characteristics were specified. The aircraft dynamic responses were quantified with natural frequencies and damping ratio targets for the Short Period, Phugoid, Dutch Roll, and spiral modes. The lessons learned from operating military aircraft led to defining distinguishing characteristics for broad classes of aircraft. Similarly, it became apparent that the requirements should be dependent on the aircraft category.[10] Updates were made to MIL-F-8785 as advances in aircraft technology expanded the variety of missions that aircraft were capable of performing, ultimately resulting in MIL-F-8785C in 1980. MIL-F-8785C was notable for incorporating the low order equivalent system (LOES) approach for evaluating complex aircraft control systems. The LOES approach reduces a high-order system response into a simpler classical system response with fewer variables and for which modal requirements for satisfactory flying qualities are well established. Using these guidelines and the requirements associated with the LOES, a designer can obtain favorable flying qualities and dynamic stability margins by matching a given aircraft's response to a target LOES response. [11]

In the 1980's, government acquisition practices underwent a change in philosophy from specifying "hard and fast" requirements to providing design guidance. The U.S. Air Force (USAF) released a new standard, MIL-STD-1797, in 1987 which allowed aircraft designers to tailor the criteria that was applicable to their aircraft. The document was amended three years later, Revision A, to be a tri-service standard. The document not only incorporated information and guidance from MIL-F-8785C, but it also included lessons learned, flight test methodologies, and the Cooper-Harper Rating Scale,[12,13] that had been widely used, but never officially adopted.[14] The Cooper-Harper Handling Qualities Rating (HQR) Scale allowed for "pass/fail" criteria when judging aircraft by using pilot opinion and the questionnaire shown in Figure 2. MIL-STD-1797 included design guidance from research conducted in the 1970's and 1980's regarding digital control for aircraft, although no single set of criteria was identified that could be applied to all aircraft. The short-term pitch response guidance in MIL-STD-1797A adds higher-order criteria for digital control systems to the LOES guidance obtained from MIL-F-8785C requirements. The additional criteria includes frequency responses using Nichols charts, Bihrle's Control Anticipation Parameter (CAP),[15] Hoh's bandwidth criteria,[16] the Neal-Smith closed-loop criteria,[17] and Gibson's time and frequency response and drop-back criteria.[18,14] MIL-STD-1797 was later reissued in 1997 as MIL-HDBK-1797, underscoring the change in philosophy from a design requirements document to a design guidance document.

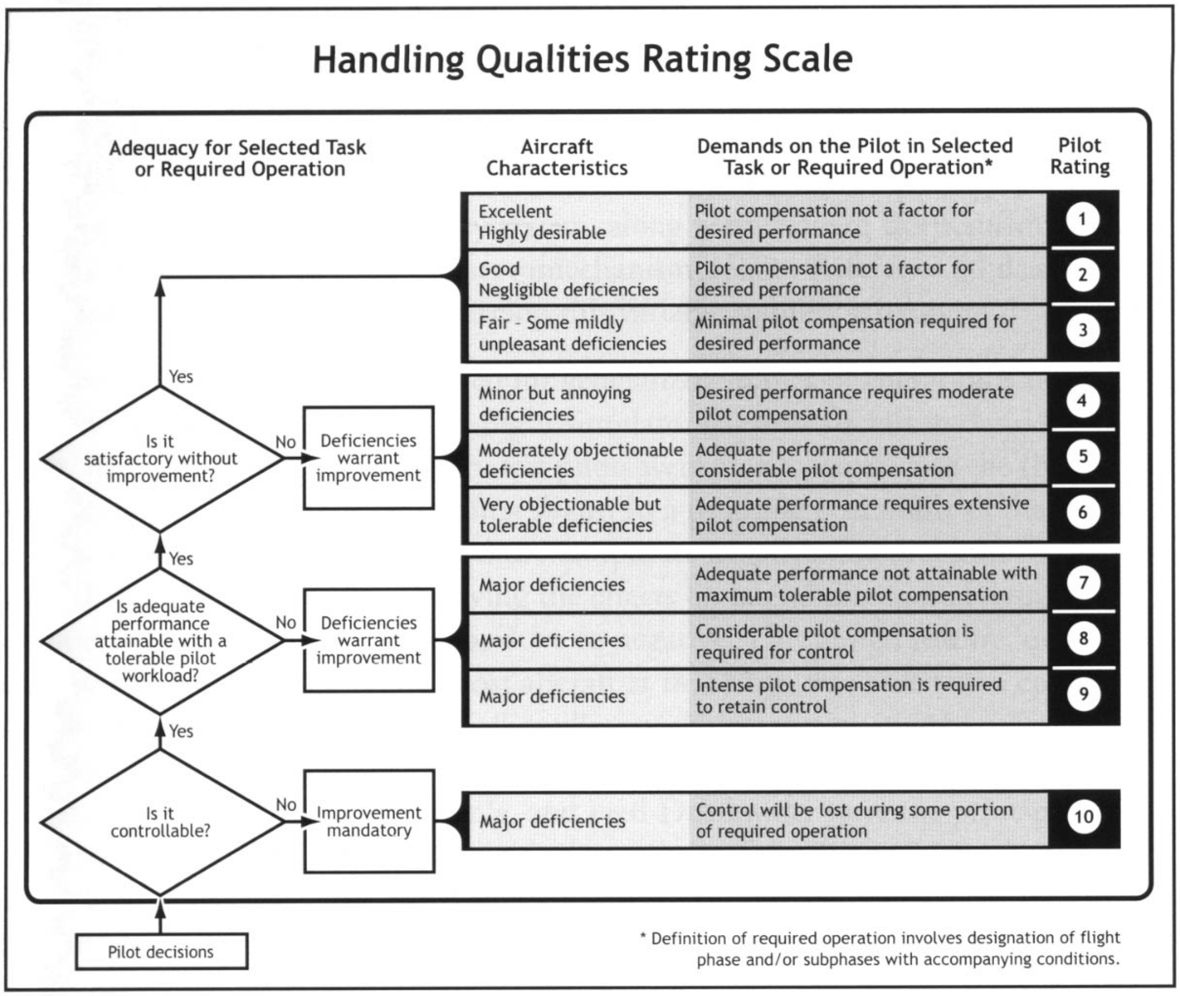

Figure 2: Cooper-Harper Handling Qualities Rating Scale[12]

Beginning in the late 1990's, the DoD released a set of Joint Service Specification Guides (JSSG) to further reform aviation acquisition strategies from a "design-to" based to a "performance based" system. Performance based approaches focus requirements only on top-level objectives while eliminating detailed requirements used in design-to strategies. The JSSGs were designed to instruct agencies on tailoring specifications for individual developmental programs. JSSG-2001 (Air Vehicle)[19] and JSSG-2008 (Vehicle Control and Management System)[20] are the pertinent guides with respect to flying qualities. Even though these documents lean towards high-level performance based specifications, the requirements for flying qualities still rely heavily on more detailed specifications as guidance – namely MIL-STD-1797. Similarly, the procuring agency and the manufacturer should use the guidance in MIL-HDBK-516 to define the airworthiness certification criteria for DoD aircraft.[21] MIL-HDBK-516 references many stability and control and flying qualities related criteria; which, in turn, use the JSSGs and MIL-STD-1797 as reference and compliance documents to aid the designer. The flying qualities community has recently moved back towards the more detailed requirements based specification models. Towards this end, MIL-HDBK-1797A was reissued by the DoD in 2006 as MIL-STD-1797B. One reason behind this switch is that flying qualities documents were still being heavily used and referenced when designing and evaluating aircraft, independent of the actual performance based requirements. The underlying flying qualities requirement remains constant: "to assure flying qualities that provide adequate mission performance and flight safety regardless of design implementation or flight control system mechanization."[22]

III. Adapting Piloted Flying Qualities Specifications to UAVs

By utilizing flying qualities criteria, a piloted aircraft designer can aid the pilot in maximizing aircraft mission effectiveness while ensuring airworthiness. Piloted requirements are based on years of experience, research, lessons learned, and collaboration between government agencies, academia, and industry using simulation and flight tests designed to narrow down the design parameters that provide Level 1, 2, or 3 flying qualities. As in the case of piloted flying qualities, the intent of UAV flying qualities is to guarantee the safety and operational effectiveness of the aircraft. Initial efforts at developing flying qualities specifications for UAVs have focused on adapting piloted specifications. This difficult process has made it clear that focused research is needed to determine which piloted requirements are applicable, which can be relaxed, which need to be tightened, and where holes remain. In fact, the whole concept of adapting specifications is open for challenge, and research may point toward the development of specifications not based on piloted aircraft at all.

A central theme in the flying qualities documents mentioned previously is that the aircraft's flight characteristics and response is tailored to optimize the pilot-aircraft interaction. The documents give no guidance for aircraft that are remotely piloted or autonomous. In response to the growing number of remotely piloted vehicles (RPVs), the USAF began an effort in the 1970's to address RPV flying qualities.[23] This study involved tailoring the standards that eventually constituted MIL-STD-1797 to RPVs. Although it did not address unpiloted aircraft, it was an initial step toward addressing the flying qualities of uninhabited aircraft.

The Navy has only recently begun to develop full system specifications for unmanned air systems (UASs). For recent acquisitions, NAVAIR has adapted piloted flying qualities specifications to set design-to (as opposed to performance based) requirements for UAVs. Requirements traceability flows down primarily from the top level requirements for airworthiness and flight clearance approval. The flight characteristics (i.e. flying qualities) requirements for the Unmanned Combat Air System – Demonstration (UCAS-D) program and the Broad Area Maritime Surveillance (BAMS) program, which were both awarded in the last year, are based on MIL-F-8785C. Adapting the piloted specification to a UAV was the first step by the Navy to define criteria for UAVs that would be "at least" as stable and controllable as a piloted aircraft of the same class. This should guarantee a safe, airworthy aircraft that will not crash due to loss of control, while providing a stable sensor platform for mission payloads. This approach was taken because the UCAS-D and BAMS aircraft are similar in size and weight to the aircraft that the piloted specifications were originally created for. Unfortunately, the assumption that an aircraft designed to manned standards will be safe and airworthy may begin to break down when applied to smaller UAVs like the Small Tactical Unmanned Aerial System (STUAS), which has a maximum takeoff gross weight of 150 lbs.

Prior attempts to define UAV flying qualities have assumed that UAVs must fly like a manned aircraft. UAV flying qualities should remain focused on achieving the required mission performance, without unnecessary constraints inherited from piloted aircraft specifications. As discussed above, the UAV requirements were tailored to the existing categories of piloted aircraft, which are only relevant to some of the existing and planned UAVs. A requirement originally defined by pilot ratings may be unnecessarily restrictive to a UAV, driving up development costs and weight. On the other hand, without a pilot in the loop, that same requirement may not be restrictive enough, allowing the UAV to have weaker stability than desired or even lose control. Requirements can not be placed on a pilot's ability to control the aircraft, so current specifications are limited to inner-loop criteria that ensure that an average pilot can safely perform the mission. However, UAV criteria can directly address the flight control system's outer-loop performance and mission sensors as a whole. In other words, UAV flight characteristics criteria can be applied directly from top level mission performance requirements and can be traded with payload requirements and capabilities to maximize mission effectiveness.

IV. Aircraft Classes, Flight Phases, Levels of Flying Qualities, and Flight Envelopes

The top level requirement in MIL-F-8785C and MIL-STD-1797B are for aircraft to have Level 1 flying qualities in the Operational Envelope, Level 2 flying qualities in the Service Envelope, and to be recoverable from the Permissible Envelope. Degradations in flying qualities are allowed in the event of failures, atmospheric disturbances, or both, as long as the probabilities of those failures and disturbances are sufficiently remote. The detailed criteria in the lower level requirements define Level 1, 2, or 3 flying qualities. In MIL-F-8785C, the detailed requirements are defined as set values; however, in MIL-STD-1797B, the detailed requirements are blank and are to be filled in, based on the suggested values and guidance, as necessary to meet mission performance objectives. Designing to these detailed requirements usually results in an airplane with acceptable flying qualities.

Detailed performance to meet Level 1, 2, or 3 flying qualities generally varies as a function of aircraft Class and flight phase. This prevents a requirement designed to enable fighter pilots to acquire targets from driving up design costs on a cargo airplane. As an example, a portion of the roll performance criteria for Level 1 flying qualities is shown in Table 1. Time to roll to a given bank angle is varied depending on the Class of aircraft and the flight phase. Larger, Class III aircraft are given more time to perform a roll than Class IV fighters.

Aircraft classes are based on size, maneuverability, and missions. Class I is for small and light aircraft such as a Cessna 172, Class II is for medium-weight, low to medium maneuverability aircraft such as a P-3, Class III are large and heavy airplanes such as a C-5, and Class IV is for high maneuverability aircraft such as a F/A-18. Flight phases are divided into three Categories: A, B, and C. Category A includes flight phases that require precision or rapid maneuvering such as combat, terrain following, or antisubmarine search. Category B includes flight phases that are not terminal and do not require precision maneuvering such as cruise and loiter. Category C contains the terminal flight phases, such as takeoff, landing, and catapult launch.

Class	Flight Phase	Roll Angle	Time to Roll
I	A	60	1.3
	B	60	1.7
	C	30	1.3
II-L	A	45	1.4
	B	45	1.9
	C	30	1.8
III*	A	30	1.8
	B	30	2.3
	C	30	2.5
IV**	A	30	1.1
	B	90	1.7
	C	30	1.1

* Low speed range only

**Low speed range only. Excluding CO and GA

Table 1: Roll performance requirements for Level 1 flying qualities. Requirements vary as a function of aircraft class and flight phase.[1]

A flying qualities specification for UAVs will have to cover a wider range of aircraft that do not fit into the existing Classes. Aircraft Classes for UAVs must account for requirements that will vary depending on:

- Expendability of the airframe and payload
- Mission performance objectives
- Potential for damage to people or property
- Airspace integration

Without humans onboard, higher loss rates than piloted aircraft may be acceptable. The preeminent consideration for airworthiness is the potential for loss of life and damaging property on the ground. Payload and airframe value can be significant considerations as well. Small and slow UAVs flown in restricted ranges have a much lower probability of hurting people if they crash than large UAVs flying in the National Airspace. For example, the Dragon Eye UAV in use by the Marine Corps weighs 5 lbs and has a wingspan of less than 4 ft. Based on its size alone, the likelihood of it causing significant damage or loss of life is minimal. At smaller sizes, design tradeoffs adding weight for additional control or redundancy may become unacceptable. Therefore, some compromises on flying qualities requirements will have to be made to keep development costs within reason. If the UAV is also deemed to be an expendable asset, then the smaller, slower types will have relaxed requirements for airworthiness. At a minimum, the requirements for expendable UAVs can be reduced to those necessary to guarantee containment of the UAV within the designated airspace. Alternatively, operating a UAV in the national airspace requires a full airworthiness evaluation that will guarantee that the UAV can sustain controlled flight throughout its entire mission. Class definitions need to be expanded to categorize UAVs with "relaxed" levels of airworthiness. Although higher loss rates may be accepted, there still may be stringent requirements for mission performance that need to be considered for Class definitions along with Flight Phases.

Another consideration is that for UAVs, ride and handling qualities are only important if they affect mission performance and safe mission completion. The definitions of flight phase categories may need to be modified, or new categories may be needed to account for UAV flight phases that have no mission performance requirements other than safe transit. New UAV missions will also require new flight phases, particularly in terminal area operations. Flight phases need to account for UAVs that launch from land and ships with catapult or rocket assists, land into nets, catch a wire, or use other new launch and recovery techniques. The classification of UAVs and definition of flight phases is important for framing a new flying qualities specification.

In general, the Operational Envelope covers altitude, airspeed, and normal acceleration (n_z) used during operational missions. More specifically, the Operational Envelope in MIL-F-8785C is where Level 1 flying qualities are required in order to perform the mission.[1] MIL-STD-1797B has essentially the same requirements for flight envelopes but calls the Operational, Service, and Permissible Envelopes the Region of Satisfactory Handling, the Region of Tolerable Handling, and the Region of Recoverable Handling, respectively, to be clearer about what is required in those regions. The Service Envelope is coincident with, or outside of, the Operational Envelope and is intended to be at the physical limits of the airplane (with margin). The Permissible Envelope encompasses the Service and Operational Envelopes, as well as anywhere that flight is allowable and possible.[1] Service and Permissible envelopes provide margin for the pilot to fly outside of the Operational Envelope as mission needs dictate and encourage gradual degradation in flying qualities to avoid cliffs that might cause sudden departures from controlled flight. The boundaries of the Service and Permissible Envelopes also allow for mission growth which frequently requires airplanes to fly missions outside the original intent of the design. The size of the Service and Permissible envelopes can be traded in the design and may affect the cost of analysis and verification.

For UAVs, it is tempting to take a more limited approach toward the definition of flight envelopes. They are flown by computers, so it is assumed that they will not fly where they are not programmed to fly – there is no pilot variability. Although there is no need for a gradual degradation in flying qualities to signal the pilot that departure is imminent, it still seems useful to have multiple flight envelopes. The Operational Envelope could be defined as where Level 1 flying qualities are needed for the mission. The Operational Envelope could be very small for specific UAV mission, but design trades should be made between the size of the envelope and mission adaptability. The Service Envelope could be where at least Level 2 flying qualities are needed and where there are physical or software aircraft limits. In most cases it would seem that software limits (e.g. an angle of attack (AOA) limiter) would be needed to protect the aircraft from the physical limit (e.g. stall). If the UAV is designed to only fly in the Operational Envelope, and if there is no need for adequate flying qualities outside of the Operational Envelope, the limits of the Service Envelope may be coincident to the operational envelope, effectively reducing the number of envelopes to two. The Permissible Envelope would provide margin around the Service and Operational Envelopes and would include all flight conditions that can be reached in failure states or environmental disturbances without causing the aircraft to crash (i.e. the recoverable flight envelope). For example, if an aircraft is operating at its minimum commandable airspeed and a gust decreases the airspeed, the aircraft will maintain control unless the airspeed goes below the limit of the Permissible Envelope. Outside of the Permissible Envelope, the operating assumption is that a UAV without upset recovery capability will crash. Unless UAVs are designed to fly anywhere and have upset recovery capability, the margin between the limits of the Service and Permissible Envelope will be critical for UAV airworthiness.

MIL-F-8785C definitions for levels of flying qualities are:

Level 1 Flying qualities clearly adequate for the mission Flight Phase.

Level 2 Flying qualities adequate for the mission Flight Phase, but some increase in pilot workload or degradation in mission effectiveness, or both, exists.

Level 3 Flying qualities such that the airplane can be controlled safely, but pilot workload is excessive or mission effectiveness is inadequate, or both. Category A Flight Phases can be terminated safely, and Category B and C Flight Phases can be completed.

Flying Qualities levels are typically determined by the quantitative specification criteria and qualitative piloted evaluation during flight and/or simulation tests using the Cooper-Harper HQR Scale. Quantitative criteria useful for design are correlated to pilot ratings. During the test, a pilot will perform a given task with targets for desired and adequate performance. The resulting HQR is determined from a combination of task performance and how difficult the pilot perceived the task to be. Therefore, the HQR for a given task depends on the airplane's flight characteristics, the pilot's skill, technique, perception of the task, experience, and the selection of desired and adequate performance objectives. In the end, HQRs define how well the airplane enables a pilot to perform a task.

For a UAV, tasks and tolerances to which a pilot must fly for desired or adequate performance can be similarly applied, but variations due to pilot performance, experience, technique, and perception are not present. The difficulty in performing that task is not evaluated, and HQR ratings are not applicable. Instead of evaluating how well an aircraft enables a pilot to perform a task, UAV flying qualities levels evaluate how well the system performs the task. In effect, flying qualities levels can be simplified from the piloted versions, and tied directly to higher level mission performance objectives. However, if system level requirements for performance are broken out between the mission sensor and air vehicle subsystems, then air vehicle flying qualities requirements will have to be traded with mission sensor performance. Whereas piloted flying qualities evaluate how well a vehicle enables a pilot to perform a task, UAV flying qualities would be an evaluation of how well a vehicle enables a mission sensor to perform its function. To allow for tradeoffs between the air vehicle and mission sensor subsystems, flying qualities specifications will need to provide flexibility and guidance in tailoring air vehicle requirements. In order to provide meaningful guidance and adequate design criteria, NAVAIR plans on conducting research into the tradeoffs between mission sensors and vehicle flying qualities.

V. Probability of Degraded Flying Qualities: Failures, Turbulence, and Gusts

MIL-F-8785C and MIL-STD-1797B specify the probability of degradation in flying qualities due to failures and atmospheric conditions. Probabilities of failure depend on system reliability, whereas atmospheric probabilities depend on the environment. This forces aircraft designers to consider the effects of failures, turbulence, and gusts on airworthiness and mission performance. MIL-STD-1797B summarizes the intent of the specifications by stating that the requirements ensure: "high probability of good flying qualities where the air vehicle is expected to be used…acceptable flying qualities in reasonably likely, yet infrequently expected, conditions…a floor to assure, to the greatest extent possible, at least a flyable air vehicle no matter what single failures occur…a process to assure all the ramifications of reliance on powered controls, stability augmentation, etc., receive proper attention."[22]

For UAVs, the same approach can be used, in which the probability of mission performance degradation, mission failure, or loss of the aircraft due to flying qualities can be quantified and analyzed. Failures that cause Level 2 flying qualities degrade mission performance, whereas Level 3 flying qualities can be considered a mission abort with safe terminal flight phases. Degradation beyond Level 3 would most likely result in loss of the aircraft. The probability of mission performance degradation or a mission abort due to failures should be based on program requirements and mission needs and can be a significant cost driver. The acceptance of probability of loss depends on requirements for airworthiness. Expensive and indispensable UAVs with critical missions will need more engineering during the development process to increase the system's reliability and safety; whereas cheap and expendable UAVs may be able to suffice by utilizing simpler aerodynamic analyses based on vortex lattice methods or computational fluid dynamics (CFD), rather than wind tunnel and flight tests. The simple methods would be used to determine the basic characteristics of the system instead of doing full performance and stability and control wind tunnel tests with high-fidelity models – greatly reducing the development costs for the UAV.

Allowable degradation in turbulence may depend on mission requirements for operating environments, or the ability of the system to recognize turbulence and fly to smoother air. For surveillance missions it may be okay to have a sensor blackout for a few minutes due to turbulence or a few seconds due to a gust, but for a target illumination mission it may be unacceptable for any loss of contact. Unlike some failures, atmospheric disturbances that cause Level 3 flying qualities do not necessarily cause mission aborts if they are short duration, whereas failures are generally more permanent and will lead to a mission abort. Therefore, the tolerance for atmospheric disturbances may be higher than for failures.

Beyond mission performance, degradations below Level 3 flying qualities are only allowed in MIL-F-8785C if the probability is extremely remote. For the flying qualities specification, this effectively means that the aircraft will lose control and crash. This requirement still applies to UAV airworthiness. Unfortunately, there is no agreed upon standard for how remote the probabilities must be. For example, the FAA uses 10^{-9} per flight hour to quantify extremely remote failures.[24] The guidance in MIL-STD-1797B provides that these Special Failure States may be difficult to predict accurately but that the identification of potential failures is an important part of ensuring safety. The acceptance of Special Failure States comes down to the airworthiness of the system and will depend on how future airworthiness processes for UAVs are written.

Airplane mishaps are caused by pilot error, system failures, atmospheric disturbances, and engineering errors. Mishap rates from pilot error are well known; unfortunately, no one knows how many mishaps that would have been caused by the latter three have been avoided because a pilot compensated. Considering the comparably high mishap rates of UAVs, it is reasonable to assume that a significant number of mishaps have been prevented by pilots' actions. With no pilot in the loop, the analysis of failures and atmospheric disturbances becomes more important to ensure airworthiness and to find engineering errors that can be corrected.

VI. Applicability of Detailed Requirements to UAVs

Detailed requirements in the piloted specifications include longitudinal and lateral-directional stability and control, takeoff and landing, recovery from stalls, spins, and out-of-control flight, characteristics of the primary and secondary control systems, and response to atmospheric disturbances. For aircraft with stability augmentation, the piloted specifications are intended to apply to the closed-loop systems, rather than the open-loop basic airframe. All requirements for a UAV must apply to the closed-loop system, unless there is a specific need to evaluate a failure state with the flight control computer disengaged. Requirements directed at the pilot-vehicle interface, such as control feel, predictable response, or maximum control force are not applicable to UAVs. Requirements that ensure margins of safety throughout the flight envelope and ensure that the flying qualities are sufficient for mission execution are applicable. However, most of these requirements need to be modified for UAVs. The research proposed by this paper will develop guidance for adapting detailed flying qualities requirements to specific UAVs of varying sizes and with varying missions and payloads.

In the course of attempting to adapt piloted specifications to UAVs, an entirely different approach that is more suitable to UAVs may become evident. For instance, is there still value in designing for a "classical" response? With the pilot out of the loop, higher level system performance requirements can be applied directly to the air vehicle system, and there can be no argument over the varying performance of pilots. An alternate vein of research proposed by this paper will focus on mission task performance; starting at the performance objective and working backwards to the vehicle design. In the end, the final UAV specification will likely be a combination of adapted piloted specifications that take advantage of the long history of piloted flying qualities research, and new performance based requirements that tie directly to system objectives while building a new research base for UAV flying qualities.

A. Static Stability

Stick-fixed and stick free static stability (i.e. AOA/speed stability) is required in MIL-F-8785C and MIL-STD-1797B for Levels 1 and 2, whereas some instability is allowed for Level 3. This is a good requirement to start with because it is not obvious that the requirement is necessary for UAVs. "The primary purpose of the static stability paragraphs of MIL-F-8785 is to prevent divergences in airspeed and AOA which remain undetected by a busy pilot so that, at worst, the airplane would end up in an unsafe flight condition or run out of control available for recovery."[25] The requirement ensures closed-loop static stability with the pilot out of the loop. Although an autonomous UAV does not have a pilot that could get distracted and fail to notice airspeed divergence, the effect of removing closed loop static stability could result in a UAV that is unstable in some portion of the flight envelope. Ensuring that the aircraft does not diverge in AOA or airspeed due to a disturbance is still necessary. Stick-fixed and stick-free are meaningless for a UAV, but replacing stick position with a fixed longitudinal command would show static stability. Obviously, allowing slight instability for Level 3 or in transonic flight is unacceptable for a UAV.

B. Response of Slow Dynamic Modes

Phugoid stability is required for piloted aircraft for Level 1 flying qualities in MIL-F-8785C, with zero damping and slightly unstable modes allowed for Levels 2 and 3. In piloted fly-by-wire aircraft, control laws can be used to effectively eliminate the Phugoid mode, so for a UAV it may seem unnecessary to include this requirement. However, there are several reasons to consider keeping the requirement. First, a requirement being "easy" to meet does not negate the need for the requirement. Second, there may be mission requirements for speed and altitude hold modes that need a heavily damped Phugoid mode. Third, it is easy to imagine that failure states may cause a Phugoid mode problem. Analysis of Phugoid dynamics is good design practice to check the effects of failures, sensor configuration, and atmospheric disturbances on Phugoid dynamics. Even though a stable Phugoid mode is certainly required for a UAV, the specific levels of damping for Level 1 and Level 2 flying are not necessarily the same as a piloted aircraft. Research is needed to determine the relationship between Phugoid damping and mission performance.

Spiral mode can be a slowly divergent mode like the Phugoid. In the piloted specifications, spiral mode instability is allowed, and Levels 1, 2, and 3 requirements are given as times to double starting from a 20 degree roll disturbance. Spiral stability must exist for an airplane without a pilot or the airplane would eventually depart and crash. Aircraft loss is prohibited by other requirements, making a spiral stability requirement effectively redundant. Despite this redundancy, there has been hesitation in removing spiral mode requirements from UAV specifications, in part because analysis of the spiral mode effectively falls out of the analysis of lateral directional stability and controls analysis and at little to no extra cost. Testing the response of the airplane to a 20 degree roll disturbance still seems like a good idea to test departure resistance, roll and directional controllers, and spiral stability.

C. Response of Fast Dynamic Modes

Short Period, Dutch Roll, and roll mode criteria for piloted aircraft are designed to ensure appropriately quick response, avoid pilot induced oscillations (PIOs), good disturbance rejection, and to guarantee that the aircraft response does not degrade the ability to command the aircraft to go where the pilot wants it to go. Piloted specifications use frequency, damping, time constants, the CAPs, Neil-Smith and Gibson criteria, and similar parameters based on years of simulation and flight experiments correlating pilot ratings to system characteristics.

Aside from ensuring that Short Period, Dutch Roll, and roll mode dynamics do not cause departures (i.e. airworthiness), it is not clear what the requirements should be for a UAV to ensure adequate safety and mission performance. Being developed from piloted tests, the existing criteria are based on correlation to task performance resulting from pilot compensation, pilot acceptance, and vehicle stability and control. On one hand, removing the pilot may lead to less stringent requirements where ride quality and the intuitiveness of the controls no longer impact HQR ratings. On the other hand, requirements may become more stringent where achieving adequate task performance has always depended on pilot compensation on top of the vehicle design. CAPs, which ensure pilots are cued properly, probably do not matter for a UAV. Alternatively, Dutch Roll damping may need to be increased for UAVs that must track targets without a pilot in the loop to handle the fine tracking task.

In the target tracking task, the level of aircraft damping needed will depend heavily on the sensor and its inherent stability. An expensive camera with gyroscopic and software image stabilization may be able to handle large oscillations in the platform. For that same mission, a cheap camera with no stabilization may have very stringent platform stability requirements. In many cases, the mission sensors have replaced the pilot as the evaluator of mission performance. Because the variability in sensors is much wider than the variability in pilots, there is more room to tradeoff aircraft platform design for stability and sensor cost. For Category A and B flight phases, the tailoring of stability and control parameters should depend on mission tasks and the requirements of mission equipment (sensors, communications, releasable stores, etc.). Research will be needed to provide requirements and guidance to UAV designers allowing for effective tradeoffs for Category A and B flight phase tasks without compromising safety. For Category C flight phases, additional research is needed to determine what fast dynamic mode response characteristics ensure safe takeoff and landing for vehicles of various sizes and differing sensing and control schemes.

D. Control

Longitudinal control requirements in piloted specifications ensure that pitch control does not limit a pilot's ability to attain all airspeeds and load factors in the flight envelope, and does not limit takeoff performance or cause over-rotation. Lateral-directional control requirements ensure that yaw and roll control allow the pilot to control sideslip and roll angle in turns and crosswinds and make sufficiently fast bank angle changes. Pitch, roll, and yaw control can be limited by aerodynamically available control power, flight control actuators, stability augmentation, and the force and response characteristics of the control stick and pedals. For a UAV, control stick force feel and pilot strength are not applicable, so a significant number of requirements go away. However, gust rejection and recovery, pitch control power, actuators, and stability augmentation will still need to be sufficient to satisfy the remaining requirements.

Some requirements on control feel and response in the piloted specs may be candidates for deletion. There are requirements for roll and pitch control linearity (and the avoidance of objectionable nonlinearities) intended to provide predictable response to a pilot. There is also a complicated set of requirements for roll-rate oscillations. Airplanes with high Dutch Roll bank angle to sideslip angle ratios ($|\varphi/\beta|_d$) and low damping tend to have oscillations in roll rate response that interferes with pilot precision.[22] In this case the piloted requirements are designed to enable the pilot to perform precise control. With the UAV control system replacing the pilot, the requirement on precise control with respect to the pilot can be applied at a higher level – directly to the flight control system. This highlights an important point: because piloted specifications cannot place requirements on pilot ability, they must require characteristics that enable average pilots to fly well. For UAVs, specifications can place requirements directly on how well the flight control computer flies the aircraft. This gap in the application of piloted specifications to UAVs is an opportunity to develop requirements directly tied to mission task performance.

Control requirements in piloted specs include prohibitions against PIOs. Although conventional PIOs are not a concern for UAVs, initial attempts at UAV specifications have included restrictions against system induced oscillations (SIOs). After some debate, it was decided for recent Navy acquisitions programs that SIO requirements should be avoided as long as stability and control margin criteria are met. These margins include, but are not limited to, surface deflection and rate limits, phase and gain margins, and physical and computational latency delays. Additional research may be advisable to determine if there would be value in applying conventional PIO analyses to unmanned systems. Two areas of focus for SIO research would be aircraft and ship airwake interaction. The dynamic environment of airwakes could provide the worst case scenario for control power margins and rate limits. Margins in piloted specifications in control power, rates, and hinge moment are critical for UAVs as they are one of the primary means of ensuring safe flight throughout the operational, service, and permissible envelopes. Assuming flight control laws are sound, ensuring margins on control rates should effectively prevent SIO. As in piloted aircraft, it is particularly important to ensure that there is adequate control margin to recover from all attainable angles of attack, stall, deep stall, and spins.

E. Takeoff and Landing

Flying qualities in Category C flight phases are critical for flight safety and airworthiness. Requirements on static stability, the fast dynamic modes, flight-path stability, control power, and control margins in Category C flight phases ensure that pilots can initiate and terminate flight safely, every time. These criteria rely on pilot's performing portions of the tasks, so UAV criteria must be adapted for not having a pilot to close the outer loops. This may mean increasing Short Period damping and frequency, reducing the roll mode time constant, or increasing control margins from piloted criteria. Control requirements will still need to ensure control power for rotation and to handle crosswinds, but pilot control force requirements are not applicable. For Category C, mission performance is not the problem and research will be focused on ensuring safe, precise, and accurate takeoffs and landings, regardless of the technique utilized by the UAV.

UAVs bring variety to Category C flight phases beyond what is currently in the piloted specifications. Current specifications account for carrier catapult launch and arresting wire recovery, wave-off, and bolter. These criteria can easily be applied to the UCAS-D since it will takeoff and land from an aircraft carrier just like an F/A-18, and will have to account for the normal manned carrier operations. However, the ScanEagle UAV can be launched from small ships using a pneumatic launcher and recovered by catching the wingtip on a vertically hung wire. The Pioneer UAV can be deck launched with a rocket assist and recovered using a net erected on the aft deck of the ship. During land-based operations, the Pioneer can perform a conventional takeoff or pneumatic launch and arresting cable recoveries, similar to a carrier arrested landing. Other UAVs can be recovered by parachute, water-based pontoon landings, belly-landings on land or water, and net recoveries on ships, land, or even on a moving truck. With the variety in Category C flight phases for UAVs, there is a significant amount of work to be performed to determine design guidance that will ensure airworthiness.

Besides the variety of launch and recovery methods, there is also a variety in launch and recovery environments. Wind-over-deck (WOD) for naval operations creates ship airwakes that must be modeled and for which UAVs must be designed. Ship airwakes can vary significantly with ship size, class, configuration, and the launch and recovery locations on the deck. For small, slow, and light UAVs, the airwake can become even more significant relative to the inertia of the aircraft. Ship air wakes are a large area of research[26] for aircraft of all types, and will be critically important in flying qualities specifications.

F. Stalls, Out-of-Control Flight, and Recovery

Like piloted aircraft, UAVs may or may not be required to recover from out-of-control flight, such as spins. Piloted aircraft have the advantage that air crews are able to recognize impending stalls or departures and avoid them, or recover once departed. Flight control assistance is sometimes provided via spin arrows and special control laws, or even automatic upset-recovery. To enable UAVs to recover, algorithms must be developed and control margins must be available. Accurate sensor data are critical to auto-recovery. Out-of-control flight tends to be a very dynamic event that requires high sensor data rates and ranges on attitude, rate, and acceleration to accurately measure the dynamics of the situation. Designing efficient and reliable upset-recovery control laws requires understanding of high AOA and departure aerodynamics gained through full envelope testing of static and dynamic stability and control derivatives. However, there are numerous UAV platforms around today for which this level of detail does not exist because the relatively cheap production costs for UAVs leads to a design-build-fly-fix philosophy, and limited development of an aerodynamic database. Likewise, the control architecture in these systems often contain “unsophisticated” control laws for only basic stabilization and navigation capabilities, not robust controllers that can prevent and/or recover from stalls and out-of-control flight.

When auto-recovery is not provided, then margins must be provided in the flight envelopes to prevent loss-of-control. For requirements development to date, it has been assumed that a loss of control results in loss of the aircraft. If stall recovery is not provided via aerodynamic design and/or flight controls, stalls are also assumed to cause loss of the aircraft. Departures or stalls in this case would only be allowed if their probability is extremely remote. This means that stability and control margins must be provided for all but the most remote atmospheric disturbances, and for all failure states except for Special Failures States (extremely remote and approved failure states allowed to cause aircraft loss). In addition to the traditionally evaluated natural atmospheric disturbances, and particularly for UAVs intending to fly in the same airspace as piloted aircraft, consideration must also be given to aircraft wake encounters. In the past, several highly sophisticated aircraft have had undesirable flight characteristics uncovered after flying into aircraft airwakes. These situations have resulted in departures from controlled flight, control surface rate limit oscillations, and PIOs. Proper design and analysis should be conducted to determine the acceptable stability and control margins and/or control law designs to handle aircraft airwakes. Ensuring appropriate margins may add requirements to air data and aircraft state sensors for accurate AOA, sideslip, airspeed, attitudes, rates, and accelerations. It remains to be seen if it will be easier to design recovery algorithms rather than providing the margin needed to be "departure-proof."

VII. NAVAIR Plan for Developing New Flying Qualities Criteria for UAVs

No single group or entity can create new design standards and criteria that successfully encompass the experience and background that is spread across the aviation community. With that in mind, the NAVAIR Aeromechanics Division is initiating research supporting the development of a flying qualities specification and design guidance for UAVs. NAVAIR's development of UAV specifications begins with research into requirements for airworthiness and mission performance. Parallel approaches are being pursued: (1) adapting detailed piloted design specifications for use by UAVs, and (2) using a new approach not found in current fixed wing specifications with mission task elements (MTEs) to directly measure flying qualities against system performance objectives. In the near term, the focus of research is limited to low maneuverability reconnaissance-type fixed wing UAVs. In the future, research will be expanded to medium and high maneuverability fixed wing UAVs, RPVs, and rotary wing UAVs.

NAVAIR is also planning separate research efforts in the following areas:

1) Adapting piloted specifications to ensure mission performance while considering air vehicle and mission payload trade-offs
2) Adapting piloted specifications for airworthiness
3) MTEs and flight test maneuvers
4) Departure resistance and upset recovery algorithms and techniques
5) Low fidelity – low cost modeling for safety assessments of expendable UAVs

NAVAIR has already begun a research effort to evaluate sensor and payload requirements and how they relate to and drive UAV flying qualities requirements. Research into airworthiness requirements has been an ongoing task as more and more UAVs have entered the system requesting various levels of certification from the Navy. In addition to these areas, NAVAIR is involved with efforts with the Society of Automotive Engineers (SAE) to define a flight controls recommended practice document. This is an effort to begin the same type of discussions with respect to UAV flight controls.

Determining appropriate requirements for airworthiness of UAVs is challenging. Failure states, flight envelopes, gusts, aircraft and ship wakes, stall, departure recovery, and stability and control margins are all areas in need of research to understand the differences between piloted and unpiloted aircraft safety. Identifying where the aircraft flies, and more importantly, where it loses control are safety-critical aspects of flight envelope definitions. Research in this area will the guide size of the margins between the Operational, Service, and Permissible Envelopes with respect to stability, control power, and control rates. Margins set in the requirements phase of a program need to account for mission growth, aging aircraft, failures, and atmospheric disturbances. Departure resistance and recovery research will also help provide guidance on the margins needed to ensure safe flight, as well as the aerodynamic data needed to accurately model the edges of the envelope and beyond.

Simulation model development is another key area to improving certification capabilities for UAVs. In many cases, NAVAIR's ability to analyze and predict the flight characteristics of UAVs relies heavily on simulation, CFD, wind tunnel testing, and other predictive methods. When little to no data is available for expendable, low-cost UAVs, NAVAIR is planning to research the feasibility of low fidelity models that enable flight dynamics performance monitors to identify risks and provide mitigation to operators. For all other UAVs the accuracy of simulation tools need to be high to ensure that systems are being tested to the most representative conditions and environments. Consequently, accurate modeling of atmospheric disturbances including gusts, turbulence, and aircraft and ship wakes (plus ship motion for operations in rough seas) has become increasingly important to developing flight control software in systems without the aid of pilot compensation. NAVAIR is currently reviewing the somewhat outdated and disorganized collection of environmental data (airwake, ship motion, turbulence, and gust models) to create a set of models that are categorized by fidelity and regions of validity.

Adapting piloted specifications to UAVs has the advantage of utilizing the wealth of existing data in piloted flying qualities. The initial tasks will focus first on understanding the applicability of the requirements, second on determining appropriate guidance for modifying the requirements for UAVs, and third structuring the requirements such that mission payload and air vehicle performance can be traded within the design. In addition to adapting piloted specifications, NAVAIR is planning to develop a task and tolerance database specific to UAVs. Mission task maneuvers and tolerances will be defined for the unique missions of the UAV systems employed today. Utilizing MTEs, similar to those defined in the rotorcraft specification ADS-33-PRF,[27] will allow UAV system specifications to be tailored to specific missions. They will also provide detailed task and tolerance guidance to assist designers and evaluators in assessing the flight characteristics of a vehicle. This approach is in line with a performance based acquisition and provides a direct link to top level mission requirements. MTEs set expectations for precision control of an aircraft, define levels of aggressiveness required to adequately stress the system, and can provide provisions for environmental conditions. MTE requirements may be met through a combination of airframe and mission payload capabilities allowing for design tradeoffs. Without a large base of experience, test data, and research on which to base a detail design-to specification like MIL-F-8785C, the MTE approach may provide a suitable alternative to ensure that user requirements are met, while building a new basis for UAV flying qualities.

One of the biggest challenges for defining UAV flying qualities criteria is the lack of a substantial database of UAV mission data, test data, lessons learned, and experience, as was available for the first flying qualities specifications in the 1940s. Piloted specifications are based on over 100 years of such data. This research will aid in the development of a database of UAV characteristics and lessons learned, as currently resides in the background documents for MIL-F-8785C[1] and for MIL-STD-1797.[22]

VIII. Conclusion

Although written in 1941, the following quote addresses the current need for UAV flying qualities research to address the growing need for UAV specific flying qualities specifications and standards:

> The need for quantitative design criterions for describing those qualities of an airplane that make up satisfactory controllability, stability, and handling characteristics has been realized for several years. Some time ago, preliminary studies showed that adequate data for the formulation of these criterions were not available and that a large amount of preliminary work would have to be done in order to obtain the information necessary. It was apparent that flight tests of the flying qualities of numerous airplanes were required in order to provide a fund of quantitative data for correlation with pilots' opinions.[5]

Direct correlations can be drawn from this statement to the status of UAVs in today's operational environments. There is a need for data and research, the types of criteria have been mapped by piloted specifications, and the desired mission performance is known; however, decades of experience, flight test data, and collective industry knowledge specifically targeting UAV flying qualities is absent. This paper discussed some of the difficulties with the method of converting piloted specifications to UAV specifications and introduced the possibility of a new type of fixed-wing flying qualities specification that utilizes mission task elements and other UAV specific characteristics. This work has also drawn attention to several areas of interest for current and future research – developing UAV mission task elements, payload/sensor and flying qualities tradeoffs, upset recovery, simulation and data analysis requirements, and cost/expendability/reliability relationships. The aviation community must work together to develop UAV flying qualities criteria that ensure acceptable mission performance and airworthiness for integration into the national airspace.

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