

End-Game Qualification Methodology for Rotorcraft Actual Navigational Performance

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ABSTRACT

We present a test and evaluation methodology for rotorcraft airworthiness qualification of actual navigational performance using statistical tolerance and techniques for bounding confidence. The methodology is intended to demonstrate qualification of tactical performance analysis via “End-Game” substantiation while ensuring an equivalent level of safety to current and future civil standards. Requirements extraction, methodology development, methodology implementation, and methodology evaluation are presented. This end-game qualification methodology is presently being used to support US Army CH-47F navigational performance testing. A follow-up paper is planned to present the results of test using the methodology, the results of evaluation for the methodology, and suggestions for methodology improvement.

REQUIREMENTS EXTRACTION

Aviation navigation is currently migrating from the legacy airway-based system to a system of free-flight navigation, necessitating a new standard of performance requirements for operation of military aircraft in civil airspace. Requirements are extracted from two operational domains. In the first, the conduct of military operations is assessed for actual navigational performance requirements, including accuracy, integrity, and continuity of weapons systems delivery. In the second, the mapping of military operations is assessed for performance-based navigational requirements in the areas of accuracy, integrity, continuity, and course definition. Assessing the mapping domain in these four areas provides due diligence by extracting requirements that are equivalent to, or exceed, the airspace

and military operational requirements, and that allow airspace authorities to comprehend the equivalency without possessing detailed knowledge of military unique sensors. For example, accuracy in military operations, when expressed in meters of spherical radius error, can be equivalently expressed as meeting or exceeding the cross-track, along-track, and vertical error components for Required Navigational Performance (RNP) in RNP-0.3 with Vertical Navigation (VNAV) per DO-236B (EUROCAE Working Group 13, 2003).

Performance-based navigation is currently experiencing drastically changing requirements and is driving requalification of the four major areas of area navigation (RNAV) performance. The requirement extraction process operates within this shifting framework, and does not address the potential security concerns associated with military operations, which have the inherent need to obscure or degrade reported positional accuracy. The requirements extraction processes covered performance-based navigation from Basic RNAV (BRNAV) (Davids, O. J., 1997) through NEXTGEN (Babbitt, J. R., 2010) with in-between steps such as Precision RNAV (PRNAV) (OST, 2005), RNP per AC 90-105 (Allen, J. M., 2009), RNP per DO-236B (EUROCAE Working Group 13, 2003), and RNP per AC 20-RNP (AIR-130, 2001).

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PRNAV (OST, 2005) and RNP-1 per DO-236B (EUROCAE Working Group 13, 2003) have similar requirements for loss of integrity and continuity to be remote, for accuracy to be within 1nm 95% of the time, and for cross-track error to be similar in course definition; but

they have differing requirements for along-track and vertical error components. RNAV (OST, 2005), RNP per AC 20-RNP (AIR-130, 2001), and RNP per AC 90-105 (Allen, J. M., 2009) set the Receiver Autonomous Integrity Monitoring (RAIM) requirements for satellite-based navigation sensors to ensure that a loss of system integrity is extremely remote. NEXTGEN (Babbitt, J. R., 2010) airspace, which is highly dependent upon performance-based navigation to provide precision position and time inputs to Automatic Dependent Surveillance and Data-link Communications, will require increased integrity and continuity of the navigation system. To operate in this NEXTGEN (Babbitt, J. R., 2010) airspace environment and maintain current manufacturer, owner, and operator liabilities to the Army, aircraft will have to perform RNP at an accuracy of 0.1nm 95% with a loss of containment or integrity decreased to extremely improbable. With orders of magnitude changes in performance-based navigation occurring, the methodology and the data from the methodology must be reusable.

METHODOLOGY DEVELOPMENT

Historically, the methodology to qualify complex systems has been to use a form of work breakdown structure to divide the system into separate testable (and presumably affordable) components or subsystems. This approach allows one-time testing or minimum sampling of production-representative items at the component, box, and subsystem levels. System-level testing is then reduced to exclude actions that would retest lower-level systems. For example, a circuit manufacturer can select a resistor from a manufacturer on the qualified product list and test the circuit functions without testing the resistor performance because the component has already undergone more extensive component qualification testing. While the design of a helicopter may seem to fit this work breakdown structure approach (e.g., the power-train subsystem consists of engine, transmission, and rotor subsystems, etc.), the actual implementation does not result in the desired reduction of testing. Because the requirement is for all subsystems to work together at the aircraft level, even if significant testing occurs at the component level, additional testing is required at each higher assembly in preparation for actual flight testing. This stair step concept of design and test relies heavily upon modeling and analysis to limit problems found in testing at each higher step, and it is deemed insufficient for the RNP requirements analysis. Actual data is needed; all models contain inaccuracies but may be useful when within known error limits. Model usage can be effective, but it must be constrained and understood. The stair step methodology requires statistical enhancement to meet the certification requirements.

The new testing methodology for the abstraction of navigational data from a device to a level of performance is best described as a statistical sampling of the performance. FAA Order 8400.12A (Stuckey, T. E., 1998) section 12c describes this test methodology and the universal

acceptability of reams of test data. Unfortunately, the production of reams of data is not acceptable in the current fiscal environment. Still, the ability to bound the actual and future data to a probability within a defined confidence interval is of critical importance to the methodology. This ability can be especially important when dealing with small data sets where several flight hours are required to obtain each data point. For example, after only two flights the mean, standard deviation (σ), and the 95% ($\approx 2\sigma$) confidence interval are known but not statistically meaningful. Maintaining 95% confidence produces a large unusable interval. Each additional test point improves the confidence of the mean, standard deviation, and the numerical limits of the 95% interval. Eventually, additional test points will only confirm that the system either passes or fails the test with ever-increasing confidence within a narrowing interval. This approach is not suitable for all component and subsystems under evaluation, so the two methodologies are combined. The problems with proving the requirement using multiple layers of confidence is bypassed through the use of tolerance limits. Tolerance limits and tolerance limit testing has achieved lasting success when used for integrity, continuity, and accuracy in propulsion parts.

Methodology development started with the development of a hypothesis: The CH-47F helicopter's RNAV total system accuracy is less than 0.3 NM error. This test of a hypothesis approach allowed an affordable verification of an existing RNAV system at the flight test level and collection of a variety of subsystem data to perform the methodology upon. This approach also allowed the Program Managers to see the advantages of the methodology and obtain preliminary accuracies toward RNP compliance before allocating design changes; larger-scoped qualification of the integrity, continuity, and course definition requirements; and update of the accuracy for the design changes. A literature search of Air Force, Navy, and industry papers on the subject revealed that accuracy data are normally distributed. Since the CH-47F is the first Army helicopter to undergo this type of test and evaluation, the sample size selection technique being used assumes an unknown distribution and an unknown variance. The analysis requirement is a 95% confidence that the error will not exceed a specified amount. This calculation yielded a sample size of just over 10 (i.e., 11) trials. The designed implementation of RNAV within the aircraft provides for five modes or five categories to analyze. Each category is unique enough to collect 11 trials in each independent category.

- Unaided: "hand-flown Course Deviation Indicator (CDI)
- Flight Director Queuing
- Autopilot "automatic flight control system"
- Maximum Degraded System
- Military Sensor in lieu of GPS Sensor

After commencing the test program, the first 11 trials will be evaluated to determine the distribution and standard deviation. A "goodness of fit" check will determine whether

the data are normally distributed. If the standard deviation exceeds the allowable error, then the system is likely to fail the entire test. If the standard deviation is within the established bounds, then the CH-47F's accuracy testing can proceed.

METHODOLOGY IMPLEMENTATION

The methodology proposed for implementation combines the analytical prediction and verification by test method historically used for qualification of complex systems with a statistical sampling of performance to reach a decision point more efficiently. The implementation of this method has three major components.

Preparatory analysis is the first component. The system design is analyzed to determine whether the RNP requirements for accuracy, continuity, integrity, and course definition are analytically achievable. This preliminary RNP analysis is a first step and can be accomplished prior to the expenditure of any scarce flight hour resources, and it provides the foundation for all future analysis. The preliminary RNP analysis not only identifies the factors that impact performance, but it also categorizes them for detailed analysis. The materiel developer can use the framework established to isolate or combine the various components for test and evaluation. This second step in the preparatory analysis can provide a myriad of opportunities based on the level of detail or specificity of the preliminary RNP analysis. Once the various subcomponents of the systems capability are defined and isolated, statistical sampling theory can be applied to scope the flight test program. For example, in the current program for unaided "hand-flown CDI," there is a need to demonstrate 11 random accuracy flight test events. Randomness here includes various unspecified times and locations with crews of Army aviators possessing various levels of skill. The effectiveness of the preparatory analysis and its impact on subsequent implementation components, as well as on portions for total test effort and potential reuse for future efforts depends upon the expertise of the systems engineers conducting the preliminary RNP analysis, the statistical process control exercised during the statistical sampling, and the art or elegance of the portion selection for evaluation.

An "end-game" accuracy flight test program is the second implementation component. This flight test program will collect the statistical data required to evaluate the aircraft requirements for accuracy, the accuracy component of integrity and continuity, and some small level of confidence toward integrity and continuity through monitoring for any failure events. The test does not address the entire flight envelope with the intent to capture and statistically define accuracy; rather, the test program selects a specific subset of flight performance where expected accuracy can be precisely predicted and where actual accuracy can be effectively measured. Thus, the previous example of 11 (i.e., more than 10) random flights under unaided "hand-flown CDI" are not performed as completely

random events because the intent is to focus more tightly on collecting the random effects of certain subsystems, rather than to conduct a generic flight under generic conditions. The accuracy flight tests are scoped to precision approaches where the required accuracy can be tightly defined and the aircraft performance can be precisely captured. The variations will be time of day, weather, and crew experience, and will include the potential for all routine flight hazards. This design of experiment also provides compatibility with future testing requirements. Eleven precision approaches are performed from the Final Approach Fix (FAF) along a glide slope though the Decision Height (DH) or Minimum Descent Altitude (MDA) slowing to hover at a specified altitude and over a fixed position. The aircraft and crew operate normally, using standard instrumentation and guidance, while the requirements and performance are defined and captured externally. A set of 11 approaches is captured for each of the five guidance modes; then additional approaches, to represent additional crew configurations, can be added in sets of less than 11, statically. If preliminary results show a significant advantage toward a specific military versus a general civil requirement, then this data set can be expanded from the current aircraft evaluation to a flight-crew-oriented evaluation of the Flight Technical Error (FTE) associated with US Army CH-47F pilots. Additionally, the captured data can be used for box-level or subsystem evaluations, which include total system error as a portion of its measurements, and can provide a valuable recursive assessment of the effectiveness of the preparatory analysis. This design of experiment for the "endgame" analysis provides defined repeatability in testing, flexibly structured results, and feedback to the preliminary RNP analysis.

The third methodology implementation component is to use the legacy qualification method with the added statistical surveys at the box and subsystem-level per the portion partitions. Even when applied iteratively, this approach allows for in-progress confirmation of the process, veracity of the implementation solution, and growth analysis. Tracking of errors is critical for this final analysis of the system. All models included in this legacy qualification must be verified and validated for the key variables under test to represent the aircraft to a high level of confidence (i.e., model xyz is useful for this test or application because the error is known or bounded). The final analysis will then mirror the preliminary RNP analysis but will have actual qualification data in place of the analytical estimates. The final analysis uses the maximum values from either the real tolerance data or from surveys or specification values. The methodology implementation brings the "end-game" into a complete package for evaluation.

METHODOLOGY EVALUATION

Using legacy evaluation techniques requires that system-level testing include both critical airworthiness criteria as well as a random selection of other criteria that were tested at the subsystem-level. These results confirm the key evaluation issues and provide a broader means of

evaluating and accepting subsystem-level testing results. Similar evaluations are to have been conducted at each subordinate level of testing where critical subsystem tests and a selection of lower-tiered tests are repeated to a depth and rigor to the evaluation. These techniques drive a sequential test and evaluation program wherein the final evaluation is only discernable late in the test program, and material developer flexibility and responsiveness are minimized.

The evaluation methodology described herein will also incur some repeat of testing at different levels, though to a lesser extent and in a more advantageous sequence. This latter is possible because the uniformity of the various populations shall be verified for the statistical surveys. When population tests cannot detect a difference between any sets of mixed data, the uniformity of the population can be validated and provides validation of the method of multiple-level tests. These populations include data sets derived from data directly measured at the system-level as well as data indirectly measured at the system-level but directly measured at the subsystem and box level during testing.

By executing this "end-game" methodology, test data distribution is also evaluated; FTE assumptions are confirmed; and applicability to Army rotorcraft is verified. In addition, the assumptions in the methodology are rechecked throughout the end-game accuracy flight test program.

The methodology described herein provides a robust design of experiment, that collects statistically sufficient data, enabling the material developer to ascertain, prior to an unrecoverable expenditure of resources, whether the system can meet the accuracy requirement or contains a design flaw.

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