Check for updates

Received: 15 July 2022 | Revised: 20 August 2022 | Accepted: 25 November 2022

DOI: 10.1002/sys.21654

REGULAR ARTICLE

WILEY

Using a run time assurance approach for certifying autonomy within naval aviation

Donald Costello[1] | Huan Xu[2]

[1]Weapons Robotics and Control Department, United States Naval Academy, Annapolis, Maryland, USA

[2]Aerospace Engineering/Institute for Systems Research, University of Maryland, College Park, Maryland, USA

Correspondence
Donald Costello, Weapons Robotics and Control Department, United States Naval Academy, Annapolis, MD 21402, USA.
Email: dcostell@usna.edu

Both authors contributed equally to this study.

Abstract

The methods and procedures within United States naval aviation to certify an aircraft safe for flight are well established. However, these methods and procedures are based on clearing a system that is operated or monitored by a human. A fully autonomous system will not have a human in or on the loop and will therefore require a new method for certifying it safe for flight. This paper details how to use run time assurance as the framework for a safety of flight certification of autonomous behavior within United States naval aviation. We present an aerial refueling task with run time assurance as use case for the framework for certification. Within the use case we then give more details on the mechanics of using RTA to enable autonomous functionality within naval aviation.

KEYWORDS
autonomy, certification, military aviation

1 | INTRODUCTION

In the United States Navy (USN), safety of flight certification authority has been assigned to the Naval Air System Command (NAVAIR). In June 2022, NAVAIR published the latest version of the USN airworthiness policies.[1] This manual standardizes the methods and processes for safety of flight certification within naval aviation. Ultimately, NAVAIR established a process where the various technical domains characterize a system against established standards to identity and mitigate risk before a system is fielded. However, the standards that the technical domains rely on have one overarching assumption: there will be a human in or on the loop when a system is operated by the USN. The future of naval aviation is uncrewed and eventually autonomous. However, before we can field these systems standards and methods of compliance need to be established for autonomous functionality. Before these standards can be established, there needs to be a clearance envelope established to enable operations while we learn more about this game changing technology.

All modern aircraft have some level of automation, which can be thought of as an autopilot or relief mode. However, all of these modes still assume a human is in or on the loop during operation. Current discussions for certification of autonomy focus on six levels of autonomy. These levels vary from level zero (no automation) to level five (fully autonomous).[2] Naval aviation certification officials have used these levels in discussions with the various aircraft program offices as we continue to field new manned and uncrewed systems. Yet, standards and methods of compliance still need to be developed for certifying a naval aviation system that could be considered level five. For the purposes of this paper we will assume that an autonomous behavior being certified will be considered level five autonomy (fully autonomous).

A fully autonomous air vehicle, one that would operate autonomous from take off to landing without a human in or on the loop, would be extremely complicated to certify as the certification process for autonomous systems has yet to be fully developed and vetted. The safety of flight certification officials are hesitant to tackle such a large problem all at once. Therefore, prior to certifying an autonomous vehicle we propose simply certifying an autonomous behavior to complete the high gain task of acting as the receiver for aerial refueling. By doing so, the safety of flight certification officials will become more comfortable with autonomy.

© 2023 Wiley Periodicals LLC. This article has been contributed to by U.S. Government employees and their work is in the public domain in the USA.

Naval safety of flight certification officials require certification evidence prior to issuing a safety of flight certification. What that evidence would consist of is yet to be determined. This paper proposes establishing a box, or clearance envelope, where the vehicle will be authorized to operate autonomously. While inside the clearance envelope it will be allowed to exhibit non-deterministic behavior (the exact behavior of the system cannot be determined based upon the input conditions). A controller will be used to continuously monitor the air vehicle to ensure it is only exhibiting autonomous behavior while it is within this box. If the position or behavior of the unmanned vehicle is no longer in the box the controller will revert the air vehicle to deterministic behavior (based on known conditions, the vehicle will exhibit a known behavior) and return to a predetermined safe location before reattempting to refuel. We will use run time assurance (RTA) to ensure the air vehicle will remain within the box, and we will develop evidence that certification officials can use when making their risk decisions.

This paper presents a formal proposal of using RTA for certifying non deterministic behavior in naval aviation within the academic community. It defines the mechanics behind using RTA for the autonomous (receiver) aerial refueling task. It further details how the clearance envelope would be demarcated, and what would happen if the receiver reached a limit of the clearance envelope. The contribution of this paper is the demonstration that a RTA can be use for certification of an autonomous system to complete the air refueling task. This could be a step towards certification of the overall system in the future.

While this paper does not highlight actual flight test data for allowing a naval system to exhibit autonomous behavior, it is a critical first step in defining a process where this functionality will be allowed to be tested and fielded. This concept was presented by the authors at XPotential 2022[3] and in the September 2022 ITEA Journal.[4] This paper is an update to previous work by the authors. The opinions and conclusions expressed in this paper are those of the authors and not those of the USN.

This paper is structured as follows. In Section 2 we discuss related literature and safety of flight certification within the USN. In Section 3 we describe how to use a form of RTA as a possible method of limited safety of flight clearance for autonomous behavior in naval aviation for aerial refueling. In Section 4 we go into detail on how the RTA would be mechanized for certification. In Section 5 we summarize our approach and recommend future work.

2 | BACKGROUND

In the words of the former chief engineer of the United States Air Force (USAF): It is possible to develop systems having high levels of autonomy, but it is the lack of suitable verification and validation (V&V) methods that prevents all but relatively low levels of autonomy from being certified for use.[5] The Air Force Research Laboratory (AFRL) funded a study asking a question regarding the state of possible processes for certification of Unmanned Aerial Systems (UASs) which employ machine learning or autonomous functionality through some sort of evidence based certification process. These categories were: Formal Methods; Requirements and Metrics; Normative Oracle Generation; CoActive Design; Implications of Learning Autonomous systems; and Modeling and Simulation (M&S) considerations for licensure of autonomous systems.[6] In the near future, certification officials will be asked to certify autonomous systems. Until the certification community develops solutions to these issues, officials will be reluctant to accept the risks autonomous air vehicle possess as there will not be a human in or on the loop to have the ultimate responsibility for the actions of the system.

Currently, formalized standards and methods of compliance do not exist for naval aircraft/systems that exhibit autonomous behavior (i.e., a system that is able to respond to situations that were not explicitly pre-programmed) as there has never been a requirement for one to be developed. Several possible approaches have been proposed, but none have been vetted through the naval flight clearance authorities.[7–9] Prior work by researchers has focused on this problem.[10–13] Several issues have been identified for certifying autonomy (i.e., the complexity of autonomous systems results in an inability to test under all known conditions, difficulties in objectively measuring risk, and an ever-increasing cost of rework/redesign due to errors found late in the V&V process[14]). The decision space for certifying a vehicle to complete all tasks assigned is extremely complex.

Schierman et al. proposed, and demonstrated through M&S, that a run time monitor can be used for an uncrewed system to protect the vehicle from unsafe situations. They pointed out that as systems become ever more reliant on software it is reaching the limit of current V&V techniques. They refer to it as a safety wrapper. While operating within the safety wrapper the primary controller controls the actions of the vehicle. Once it reaches the wrapper, the fail-safe or backup controller takes over.[15] We propose a similar approach for certifying an unmanned air vehicle to act at the receiver. Providing it is within a defined envelope the onboard controller will allow it to exhibit autonomous (or non-deterministic) behavior. Once it reaches an edge of the envelope it would revert to deterministic behavior. RTA seems to be a prime candidate for certification within naval aviation. However it will require the safety of flight certification officials to think differently as they will not have enough evidence to verity exactly what the vehicle will do under every possible condition.

Current NAVAIR processes require all possible conditions be tested to properly characterize a system prior to certification. It can be thought of as analyzing the system to determine what it will do. However, the sheer volume of these conditions for an autonomous system make this resource prohibitive (both in time and financial cost). What if we can shift the paradigm to what the system will not do? If we can define a box where a system will be allowed to exhibit autonomous behavior we may have a path to a safety of flight certification. If a controller can use RTA to ensure the air vehicle remains within a clearance envelope, certification may allow autonomous behavior within naval aviation.

The certification process for naval aviation involves the technical domains evaluation of the system under test against established standards via methods of compliance to identify and eventually mitigate risk. The risk is then accepted or rejected at the appropriate level prior

15206858, 2023, 3, Downloaded from https://incose.onlinelibrary.wiley.com/doi/10.1002/sys.21654 by University Of Maryland, Wiley Online Library on [03/05/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

to a safety of flight certification.[1] We propose the use of RTA to establish a clearance envelope where an uncrewed system will be allowed to exhibit autonomous behavior. The will allow the behavior to be studied and hopefully generate standards which will allow the clearance envelope to be enlarged and eventually be the same as envelops that are used for qualified pilots.

Autonomous aerial refueling has been seen as a fertile ground for academic research, as every stage in the refueling process offers the ability to obtain publishable results. Using a global navigation satellite system, such as the United States' Global Positioning System (GPS), to provide relative positions between two aircraft has been seen as viable method for an uncrewed aircraft to fly close formation with another air vehicle.[16,17] The demonstration of computer vision to identify objects has been a staple of the research community for a number of years.[18,19] Research has been done to train a neural network to identify a drogue,[20] and to anticipate the movement of the drogue as the receiver approaches contact.[21] Several papers have been published that demonstrating the use of computer vision to identify, range, and continuously track a drogue by an UAV.[20,22–27] Finally, putting all of the parts of the refueling process together was demonstrated by the 2006 National Aeronautics and Space Administration (NASA)/ Defense Advance research Projects Agency (DARPA) program.[28] However, a method for certifying an uncrewed system to autonomously complete the aerial refueling within the USN does not currently exist.

3 | APPROACH

As a first attempt to obtain a safety of flight certification for autonomous behavior within naval aviation, we opted to analyze the aerial refueling task. This high gain task is currently carried out by fully qualified pilots and is considered a perishable skill (i.e., a skill that requires recent experience for proficiency). In addition to their initial qualification during training, pilots are required to maintain refueling currency before completing transoceanic flights.[29] Examining this task by an uncrewed system is not a new idea. Two examples of uncrewed aircraft completing this task are the 2006 NASA/DARPA study[28] and the 2015 X-47 program[30] completed by NAVAIR. However, both programs were completed under an intern flight clearance (IFC) that was tailored for a flight test demonstration program. There were numerous risk mitigation steps put into them, and a human was either in or on the loop. Our approach is designed to develop a method of obtaining a permanent flight clearance (PFC) that will not require an exorbitant amount of risk mitigation steps.

Aerial refueling is considered to be a force multiplier for military aviation. It allows an aircraft to remain airborne longer or it can extend its range. The USAF uses a flying boom to refuel their aircraft. When using the USAF method an aircraft will position itself below the tanker aircraft and allow a boom operator to plug the boom into the receiver to aerial refuel. The USN uses the North Atlantic Treaty Organization (NATO) standard for aerial refueling. It is commonly referred to as probe and drogue refueling. For this method the tanker aircraft streams a hose connected to a drogue, via a coupler, behind itself. The

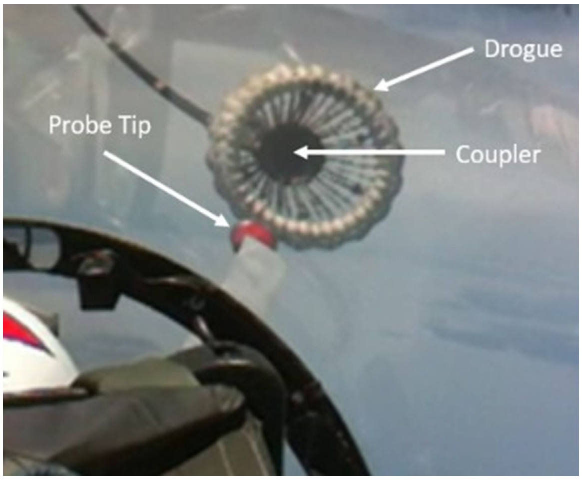

FIGURE 1 F/A-18F Super Hornet preparing to aerial refuel with key elements identified[31]

receiver aircraft then maneuvers behind the drogue and attempts to place its probe tip into the center of the coupler. Once the receiver aircraft is latched into the coupler the receiver will push the drogue forward to enable fuel transfer. During refueling the pilot needs to place the refueling tip into the center of the coupler with less then 4 inches of error to ensure contact. If outside of 4 inches, the probe tip may engage the drogue itself and proper contact with the coupler is unlikely. Figure 1 highlights the drogue, coupler and probe tip.

Before we can begin discussing the methods for achieving an airworthiness certification for autonomous behavior during aerial refueling, we must first define several check points currently used during aerial refueling. The pre-contact position is defined as a point 5–20 feet directly aft of the refueling drogue. The contact position is defined as the point where the refueling probe tip is securely lodged into the drogue coupler. The refueling point is defined as a point where the refueling hose has been pushed in, nominally to feet 10 ft, and fuel begins to transfer. As detailed in Section 2, current certification standards are based on defining what a system will do. An RTA approach to certification of autonomy will most likely required a paradigm shift to define what an autonomous system will not do. We believe that the key to obtaining a PFC for autonomous tanking is to establish a clearance envelope where the system will be permitted to exhibit autonomous behavior where a monitor will ensure it will remain within the envelope. It would include the nominal location of the drogue and the nominal location of the optional refueling point (approximately 10 feet forward of the contact position). The clearance envelope should be large enough to allow some minimal off nominal conditions to be accounted for during autonomous operations. A proposed descriptions of this clearance envelope is discussed in Section 4.

Under this approach, a controller would be required to monitor the autonomous behavior of the uncrewed system. This monitor will only allow the air vehicle to exhibit autonomous behavior when the constraints of the envelope are satisfied. Figure 2 details the proposed RTA architecture for clearing autonomous behavior within naval aviation. In the beginning the process the current aircraft state, and a

15206858, 2023, 3, Downloaded from https://incose.onlinelibrary.wiley.com/doi/10.1002/sys.21654 by University Of Maryland, Wiley Online Library on [03/05/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

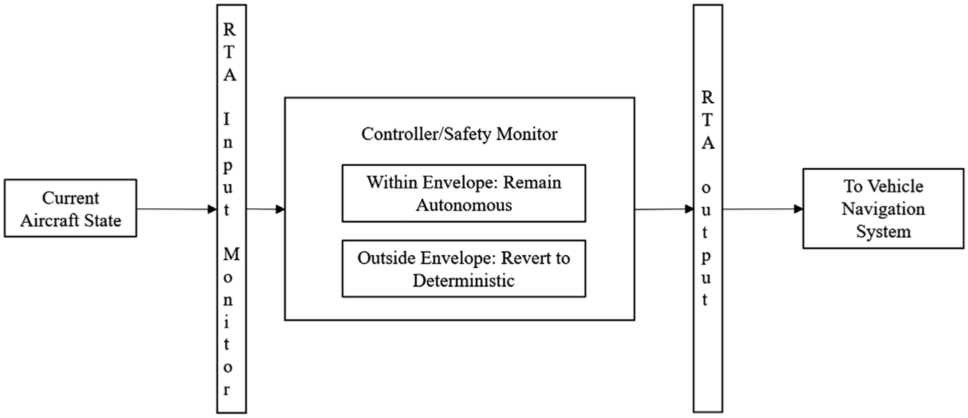

FIGURE 2 RTA architecture overview

FIGURE 3 EA-18G Growler at the pre-contact position in 2013 behind a KC-135[32]

projection into the future, is passed to the RTA input monitor. Then the controller/safety monitor determines if the air vehicle will violate the clearance envelope for autonomous behavior. The main concern when refueling is to maintain separation between the two aircraft. The safety monitor in Figure 2 will continuously track the current and projected position of the probe tip. If it were to violate the clearance envelope it would switch the air vehicles guidance to deterministic behavior and return the air vehicle to pre-contact. Provided the probe tip remains within the envelope, the monitor will allow the system to exhibit autonomous behavior.

A refueling drogue is designed to be flown within an airspeed envelope that will overlap the tanker and receiver aircraft. Based on this airspeed and aerodynamics of the refueling drogue, it should be in a predictable position relative the the tanker aircraft. As demonstrated in the NASA study and the X-47 program,[28,30] data links can be used to put the refueling aircraft into a pre-contact position. Figure 3 illustrates the pre-contact position behind a wing pod of a KC-135.

However, for a successful engagement of the refueling drogue the probe tip needs to contact near the center of the coupler behind the drogue with minimal error. The bow wave generated by the receiver aircraft, in conjunction with air turbulence, can cause perturbations in the basket during the approach to contact phase. Due to these perturbations prior demonstration programs have focused on having a human in or on the loop to ensure the uncrewed system correctly identified/tracked the drogue, and maintained a safe approach via a vision based system.

Prior research has shown that a tactical jet can maintain close formation based on a data link.[28] With current GPS technology and data processing techniques it should be possible for an autonomous aircraft to determine it location relative to the tanker aircraft with precision. The onboard processor should be able to determine the location of the probe tip relative to tanker aircraft. Providing the prob tip remains within the proposed clearance envelope the autonomous air vehicle will be allowed to exhibit non-deterministic behavior. If it were to violate the clearance envelope, the controller would revert the uncrewed system back to the pre-contact point. This approach can be considered RTA and may allow the safety of flight certification officials to grant a flight clearance for autonomous behavior within naval aviation. This is an adaptation of the RTA approach outlined in Ref. 15 where the researchers use the method to allow experimental flight controls to be studied to keep the vehicle from violating safety critical parameters.

This approach may not lead to a PFC for all phases of flight. However, it has been vetted and deemed a likely method for clearing a limited envelope for autonomous behavior by fight clearance experts across the United States Department of Defense, NASA and industry. This approach also has some limitations. At a high level, it may appear that this approach will cover all possible contingencies. However, there are edge cases that need to be evaluated prior to a fleet flight clearance. Some of them include various emergency considerations, hardware malfunctions, sensor limitations, and the ever present threat of a cyber intrusion.

4 | PROCESS FOR ALLOWING AUTONOMOUS BEHAVIOR

As discussed in Section 3, this paper proposes a RTA based approach for clearing autonomous behavior during probe and drogue aerial refueling. This Section will define the envelope that we will allow autonomous

15206858, 2023, 3, Downloaded from https://incose.onlinelibrary.wiley.com/doi/10.1002/sys.21654 by University Of Maryland, Wiley Online Library on [03/05/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

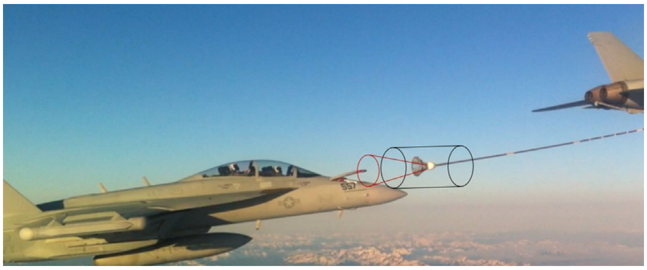

FIGURE 4 EA-18G Growler at the pre-contact position with a proposed clearance envelope superimposed on the image[33]

behavior (Section 4.1), further define a tanker relative clearance envelope behind a F/A-18 tanker aircraft that will be used to allow the computer vision system to identify the drogue (Section 4.2), define a drogue relative envelope that will also be used to allow the air vehicle to guide itself (Section 4.3), and define how the autonomous receiver aircraft will revert to deterministic behavior once it violates an edge of its clearance envelope (Section 4.4).

4.1 | Clearance envelope

When attempting to aerial refuel the pilot of a manned aircraft needs to keep two distinct items in their field of view and account for them when maneuvering during the refueling evolution. The first is the tanker aircraft. The second is the drogue itself. Prior to being cleared to enter the pre-contact position, the receiver pilot will be expected to maintain standard formation positions relative to the tanker.[29] Once the receiver is cleared to pre-contact, and eventually contact, the receiver pilot is required to maneuver their aircraft with respect to a drogue that is being dragged behind the tanker tanker aircraft.

Prior work has demonstrated that an uncrewed vehicle can maintain proper formation positions relative to the tanker aircraft.[30] Prior work has also demonstrated that an aircraft can be maneuvered via differential GPS into the refueling drogue under an IFC.[28] For our use case of autonomous behavior during the probe and drogue aerial refueling task, we propose a clearance envelope where an uncrewed vehicle can exhibit autonomous behavior. To mirror manned receiver aircraft, this clearance envelope would need to be defined from the tanker aircraft (Section 4.2) and from the refueling drogue (Section 4.3). Figure 4 depicts an EA-18G preparing to refuel from of a F/A-18. A notional envelope for a computer vision system to be allowed to search for a drogue is based on the tanker aircraft (black cylinder). A notional envelope for the guidance system is allowed to move the receiver aircraft based is on of the identified drogue (red cone).

4.2 | F/A-18 tanker corridor of autonomy (COA)

When building the envelope for autonomous refueling, the first step it to limit the area where the computer vision system will be allowed to examine to define where the refueling drogue is located. For this part

FIGURE 5 F/A-18 Equipped with an ARS pod streaming a drogue behind it with Approximate dimensions labeled[34]

FIGURE 6 F/A-18 Equipped with an ARS pod streaming a drogue behind it with our proposed COA labeled[34]

of the envelope we propose a corridor of autonomy (COA). Once the uncrewed system reaches the pre-contact point the RTA monitor will only allow the vision system to identify a drogue that is within the COA.

The standard aerial refueling platform used within the USN carrier air wing is the F/A-18. When used in the tanker role it is equipped with air refueling store (ARS) on center line. We propose a COA based off an ARS equipped F/A-18. The ARS pod has a 50 -ft hose attached to a refueling drogue. During operations, the ARS pod streams 43 foot of hose into the slip stream.[29] The actual position of the refueling drogue is based on a function of the tanker aircraft's airspeed. For the sake of this research we will assume the nominal position of the refueling drogue is 5 feet down and 42 feet directly aft of the end of the ARS pod (Figure 5).

For the sake of this paper we assume that a receiver aircraft can define a point relative to the tanker aircraft within 4 inches using a differential GPS solution. As the F/A-18 refueling drogue is 24 inch diameter[29] we shall define a circle with a 5 foot radius from the optimum refueling point. We then will define the COA by moving the near and far end of the corridor 10 feet from the optimal refueling point (Figure 6). When autonomous aerial refueling, we propose that the receiver aircraft will only identify something within the COA as a drogue to attempt contact.

The COA is defined relative to the tanker aircraft via differential GPS. This will give the receiver aircraft the ability to identify an approximate location where the drogue should be under nominal conditions based off a known airspeed. This will limit the amount of false positive results from the computer vision system.

15206858, 2023, 3, Downloaded from https://incose.onlinelibrary.wiley.com/doi/10.1002/sys.21654 by University Of Maryland, Wiley Online Library on [03/05/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

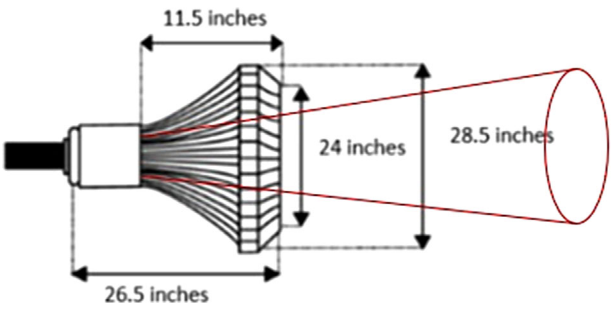

FIGURE 7 F/A-18 refueling drogue and coupler wire diagram from the Standards Related Document[29] with a notional COH added in red

4.3 | Cone of happiness (COH)

While the COA is defined based off the location of the tanker aircraft, the actual position of the drogue will vary as it is dragged through the air stream. We propose the use of computer vision to identify and tack the drogue prior to making contact with the coupler. When a human maneuvers their aircraft into contact they maintain some sort of safety margin. The closer to the coupler, the smaller that margin is. An acceptable misalignment at 10 feet from contact will be dramatically larger than an acceptable misalignment at 5 inches from contact. We propose a similar method for building the clearance envelope where an autonomous air vehicle will use its sensors to guild the aircraft into the coupler.

For the purposes of this concept, we propose the use of a Cone of Happiness (COH). This cone will extend from the edge of the coupler, which has a 8 in diameter, outwards. Providing the autonomous air vehicle can maintain its probe tip within the COH, it will be permitted to continue autonomous aerial refueling (Figure 7). The actual dimensions of the COH will need to be defined during flight test.

4.4 | Relating the COA and the COH to RTA

The first time a system is certified to exhibit autonomous behavior within naval aviation will require a restrictive flight clearance envelope. We have proposed the use of a COA for where a system will be allowed to identify a drogue behind a tanker aircraft. We further identified a COH where the refueling aircraft will be allowed to guide its refueling probe within.

We are proposing the use of an RTA architecture as follows:

- We will only allow the autonomous air vehicle to identify a drogue if it is within the COA. If it were to identify something that was not in this corridor as a possible drogue, it would disregard it (i.e., the exhaust nozzles of the F/A-18).
- We will only allow the autonomous air vehicle to physically move itself autonomously if the probe tip remains within the COH. It were to violate this restriction it would reduce airspeed and return to the pre-contact point.

We believe that by establishing a clearance envelope where an autonomous system will be allowed to exhibit autonomous behavior, we can use RTA to return the system to deterministic behavior when required.

5 | CONCLUSION AND FUTURE STEPS

This paper has proposed a method for certifying autonomous behavior within naval aviation for a limited task. It involves developing an envelope that would allow an uncrewed system to exhibit autonomous, or non-deterministic, behavior providing did not violate the edges of the envelope. It if were to violate the edges of the envelope the proposed RTA architecture would revert the navigation system to deterministic behavior and return to a know safe position relative to the tanker aircraft.

Defining this envelope is just a first step. Before a safety of flight clearance can be issued for autonomous behavior there needs to be an establish standards and methods of compliance within naval aviation. There also needs to be a tailored processes that address the unique aspects of autonomous functionality (approving a system to operate without a human in or on the loop). In particular design standards (hardware and software) including safety objectives and safety monitors need to be established and vetted by Naval Technical Area Experts (TAEs). These TAEs will need to be consulted to determine the verification and validation standards, methods, and process. Through their guidance certification data products/artifacts (evidence) need to be defined that will enable the TAEs to make informed risk decisions during the safety of flight clearance process for an autonomous system. Future research that can help address the critical path for certifying autonomy within United States naval aviation are already late to need.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

ORCID

Donald Costello https://orcid.org/0000-0003-3495-7655

REFERENCES

1. NAVAIRINST 13034.1G, Airworthiness Policy; 2022.
2. Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles; 2021. On-Road Automated Driving (ORAD) committee.
3. Costello D, Xu H. Run Time Assurance Approach to Certifying Autonomy within Naval Aviation. In: Xponential 2022; 2022.
4. Costello D, Xu H. RTA approach to certifying autonomy within USN aviation. *Int Test Eval J*. 2022; 43(3): 165–173.
5. Donley MB, Schwartz NA. Technology Horizons, A Vision for Air Force Science and Technology 2010-30. Office of the US Air Force Chief Scientist; 2010. Available from: https://apps.dtic.mil/sti/pdfs/ADA562237.pdf
6. Tate DM, Grier RA, Martin CA, Moses FL, Sparrow DA, Edmonson JR, et al. A Framework for Evidence-Based Licensure of Adaptive

15206858, 2023, 3, Downloaded from https://incose.onlinelibrary.wiley.com/doi/10.1002/sys.21654 by University Of Maryland, Wiley Online Library on [03/05/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Autonomous Systems: Technical Areas. Institute for Defense Analyses, IDA Paper P-5325, Log H 16-000680; 2016.
7. Ashokkumar CR, York GW. Trajectory Transcriptions for Potential Autonomy Features in UAV Maneuvers. In: AIAA Guidance, Navigation, and Control Conference; 2015.
8. Humphreys CJ, Cobb R, Jacques DR, Reeger JA. Dynamic Re-Plan of the Loyal Wingman Optimal Control Problem. In: AIAA Guidance, Navigation, and Control Conference; 2016.
9. Avram R, Zhang X, Muse JA, Clark M. Nonlinear Adaptive Control of Quadrotor UAVs with Run-Time Safety Assurance. In: AIAA Guidance, Navigation, and Control Conference; 2017.
10. Costello DH, Xu H. Generating certification evidence for autonomous aerial vehicles decision-making. *J Aerospace Info Sys*. 2021; 18(1): 3–13.
11. Costello DH, Jewell J, Xu H. Autonomous flight-test data in support of safety of flight certification. *J Air Transportation*. 2021; 29(2): 93–106.
12. Costello DH, Xu H. Relating sensor degradation to vehicle situational awareness for autonomous air vehicle certification. *J Aerospace Info Sys*. 2021; 18(4): 193–202.
13. Costello D. Certifying an Autonomous System to Complete Tasks Currently Reserved for Qualified Pilots. University of Maryland, College Park; 2020.
14. Clark M, Alley J, Deal PJ, Depriest JC, Hansen E, Heitmeyer C, et al. Autonomy Community of Interest (COI) Test and Evaluation, Verification and Validation (TEVV) Working Group: Technology Investment Strategy 2015-2018. Institute for Defense Analyses; 2015.
15. Schierman J, Ward D, Dutoi B, Aiello A, Berryman J, DeVore M, et al. Run-Time Verification and Validation for Safety-Critical Flight Control Systems. In: AIAA Guidance, Navigation and Control Conference and Exhibit;. Available from: https://arc.aiaa.org/doi/abs/10.2514/6.2008-6338
16. Liu K, Moore C, Buchler R, Bruner P, Fax A, Hinchman JL, et al. Precision relative navigation solution for autonomous operations in close proximity. In: 2008 IEEE/ION Position, Location and Navigation Symposium; 2008: 1246–1251.
17. Xu W, Luo D, Yang L, Wu S. Guidance Law Research for Autonomous Aerial Refueling of UAV. In: 2013 IEEE International Conference on Cyber Technology in Automation, Control and Intelligent Systems; 2013: 440–445.
18. Lange S, Sunderhauf N, Protzel P. A Vision Based Onboard Approach for Landing and Position Control of an Autonomous Multirotor UAV in GPS-Denied Environments. In: 2009 International Conference on Advanced Robotics; 2009: 1–6.
19. Liu Yc, Dai Qh. Vision aided unmanned aerial vehicle autonomy: An overview. In: 2010 3rd International Congress on Image and Signal Processing. vol. 1; 2010: 417–421.
20. Wang X, Dong X, Kong X, Li J, Zhang B. Drogue detection for autonomous aerial refueling based on convolutional neural networks. *Chinese J Aeronautics*. 2017; 30(1): 380–390.
21. Dai X, Wei Z, Quan Q. Modeling and simulation of bow wave effect in probe and drogue aerial refueling. *Chinese J Aeronautics*. 2016; 29(2): 448–461.
22. Zhi J, Dong X, Kong X, Wang X. Drogue recognition and location for UAV autonomous aerial refueling based on camera calibration. TCCT, CAA; 2014: 624–629.
23. Xufeng W, Xinmin D, Xingwei K. Feature recognition and tracking of aircraft tanker and refueling drogue for UAV aerial refueling. IEEE; 2013: 2057–2062.
24. Wang X, Kong X, Zhi J, Chen Y, Dong X. Real-time drogue recognition and 3D locating for UAV autonomous aerial refueling based on monocular machine vision. *Chinese J Aeronautics*. 2015; 28(6): 1667–1675.
25. Duan H, Li H, Luo Q, Zhang C, Li C, Li P, et al. A binocular vision-based UAVs autonomous aerial refueling platform. *Sci China Info Sci*. 2016; 59(5): 228–234.
26. Tandale MD, Bowers R, Valasek J. Trajectory tracking controller for vision-based probe and drogue autonomous aerial refueling. *J Guidance Control, Dynamics*. 2006; 29(4): 846–857.
27. Martinez C, Richardson T, Thomas P, Du Bois JL. A vision-based strategy for autonomous aerial refueling tasks. *Robot Autonomous Sys*. 2013-08-01;61(8).
28. Schweikhard K. Results of NASA/DARPA automatic probe and drogue refueling flight test. In: SAE Guidance and Control Subcommittee Meeting, Williamsburg, VA; 2006.
29. ATP-3.3.4.2.(D), US standards related document (SRD). NATO Joint Airpower Competence Center; 2022. Available from: https://coi.japcc.org/app/uploads/US-National-SRD.pdf
30. Photo Release – X-47B Unmanned Aircraft Demonstrates the First Autonomous Aerial Refueling; 2015. Available from: https://news.northropgrumman.com/news/releases/photo-release-x-47b-unmanned-aircraft-demonstrates-the-first-autonomous-aerial-refueling
31. Costello D. F/A-18F Preparing to Aerial Refuel Over Maryland; 2010. From the private collection of CDR Costello.
32. Costello D. EA-18G at the Pre-Contact Point Behind a KC-10 over Afghanistan; 2013. From the private collection of CDR Costello.
33. Costello D. EA-18G Completing the Aerial Refueling Task over Washington States; 2021. From the private collection of CDR Costello.
34. Costello D. F/A-18 Tanker Aircraft Airborne over Washington State;. From the Privite Collection of CDR Costello.

AUTHOR BIOGRAPHIES

Donald Costello received the B.S. in systems engineering from the United States Naval Academy in Annapolis, MD in 2000, the M.A.S. in aeronautical science from Embry Riddle Aeronautical University in Daytona, FL in 2005, the M.S. in aeronautical engineering from the Air Force Institute of Technology in Dayton, OH, in 2008, the M.S. in systems engineering from the Naval Post Graduate School in Monterey, CA in 2010, and the Ph.D. degree in mechanical engineering in College Park, MD in 2020. In 2008 he graduated from the United States Naval Test Pilot School and was designated an Engineering Test Pilot. He is currently an Adjunct Associate Professor at Embry Riddle Aeronautical University where he has been teaching since 2006. He joined the United States Naval Academy faculty in 2021 and serves as an assistant professor/permanent military professor in the Weapons, Robotics and Control Engineering Department where is currently associate chair. His research interest includes certification and development of autonomous systems for practical use, unmanned aerial refueling and unmanned carrier aviation.

Huan Xu received the B.S. in mechanical engineering from Harvard University in Cambridge, MA in 2007, and the M.S. and the Ph.D. degree in mechanical engineering from the California Institute of Technology in Pasadena, CA in 2008 and 2013. She joined the University of Maryland, College Park in 2013 where she is

15206858, 2023, 3, Downloaded from https://incose.onlinelibrary.wiley.com/doi/10.1002/sys.21654 by University Of Maryland, Wiley Online Library on [03/05/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

now an Associate Professor in Aerospace Engineering with a joint appointment in the Institute for Systems Research and a member of the Maryland Robotics Center. Her research interests include controls and dynamical systems, safety certification for autonomous systems, and multi-agent control.

How to cite this article: Costello D, Xu H. Using a run time assurance approach for certifying autonomy within naval aviation. *Systems Engineering*. 2023;26:271–278. https://doi.org/10.1002/sys.21654

15206858, 2023, 3, Downloaded from https://incose.onlinelibrary.wiley.com/doi/10.1002/sys.21654 by University Of Maryland, Wiley Online Library on [03/05/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License