Looking to the Future:
A Call to Action for Advanced GNC Algorithm Verification and Validation

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1. Executive Summary

Future space systems will rely on autonomous Guidance, Navigation, and Control (GNC) functions to efficiently manage safe and precise self-directed operations in uncertain complex environments. Fundamentally, the GNC system plays a key role in mission performance and safety because it computes the ideal trajectory (Guidance), determines the actual trajectory (Navigation), and executes the ideal trajectory (Control) of a vehicle's position and attitude. Our current GNC systems are highly automated and already have a high degree of complexity. As missions become more ambitious, GNC systems for launch vehicles and space platforms (e.g., spacecraft, probes, and landers) will require higher levels of performance and autonomous operation than previously encountered, for example, this includes GNC for optimizing aerodynamic and/or propulsion performance during planetary entry. This GNC Verification and Validation (V&V) paper highlights concerns with what undoubtedly will be a trend towards increased complexity as fully autonomous GNC systems are developed for future space missions. Clearly, complex GNC systems pose challenges in the prelaunch V&V phase, which is a relatively expensive part of a mission's life cycle. Essentially the V&V phase is focused on checking that the system effectively meets all the design and operational requirements for the mission.

The authors of this paper (i.e., the Inter-Agency Working Group of GNC subject matter experts) focused on this fundamental question over the past few years: ***Will the GNC engineering community of practice be sufficiently prepared to perform the necessary V&V on evolving GNC architectures that are driven by very demanding requirements for autonomy, resiliency, reconfigurability, adaptability, and mission cost-benefit balance?*** It is the viewpoint of our Inter-Agency team that the GNC V&V approaches and processes needed to address the next generation of complex GNC systems, which likely will employ various forms of modern GNC technology, are not currently established to the level the community will need in the future. While researchers and practitioners have made some progress in developing new GNC V&V methods for modern GNC systems, a good deal of work remains to be done to codify such methods in a comprehensive and systematic manner. Thus, the Inter-Agency team's partner organizations [the National Aeronautics and Space Administration (NASA), the European Space Agency (ESA), the National Centre for Space Studies (CNES), the German Aerospace Center (DLR), the French Aerospace Lab (ONERA), and ISAE-SUPAERO] have conducted preliminary investigations into advancing GNC V&V techniques, which resulted in the identification of the need for education, new V&V tools, and benchmark problems for the GNC community. The necessary proactive steps to be taken to meet the challenges and fill the gaps in GNC V&V are summarized in this paper. The first steps include identifying advanced analysis tools, developing a GNC V&V roadmap, and expanding education and training programs for GNC practitioners. This paper is a call to action and proposes a comprehensive set of recommended actions for all our stakeholders: space agencies, researchers, and industry.

2. Nature of the Problem/Issue

The authors representing the GNC discipline across space agencies and laboratories in Europe and the United States have a strong interest in the Research and Development

(R&D) of algorithms and corresponding V&V methods, tools, and processes for autonomous GNC systems. Beyond considering the strategic forward-looking R&D aspects, the GNC practitioners and leaders have the challenging responsibility of architecting, designing, developing, verifying, validating, launching, and operating spaceflight systems. Furthermore, the space agencies and laboratories often serve as a bridge between the autonomous algorithm developers in the R&D community (both in academia and institutional research laboratories) and our industry counterparts, who subsequently infuse the advanced algorithms into their applications. Note that, while Hardware-in-the-Loop (HIL) testing is an important and frequently used form of GNC V&V, the focus of this paper is on the V&V of GNC algorithms and therefore the consideration of HIL validation testing is excluded from consideration herein. The same applies to component hardware validation and full-up end-to-end system V&V.

Many future missions will have demanding new requirements for onboard autonomy, optimization, adaptation, and fault-tolerant operations. There are many examples of future missions that will drive advanced, nontraditional GNC system design, including earth observation satellites, planetary robotic and human landers, planetary and small body sample return missions, in-orbit servicing, in-orbit assembly and manufacturing, advanced launch systems, and time & cost-optimized space systems.

That last category of time & cost-optimized space systems is represented, in part, in the "New Space" environment in which there is a deliberate movement towards an alternative space business model, mainly pioneered by industry. This New Space model will increasingly influence the commercial space market, often with limited time and resources for GNC V&V efforts and with less costly Commercial-Off-the-Shelf (COTS) approaches. In the process of adopting this New Space approach to obtain affordability benefits, there are inevitable questions and concerns about the potential risks and potential impacts to overall system reliability, due to reductions in traditional levels of GNC V&V, as well as impacts on space sustainability and the overall space ecosystem. Note that the commercial space arena has already produced a disruptive, never-seen-before, innovative transition in autonomous space vehicle precision landing systems for reusable "fly-back" rocket stages in advance of space agencies and competitors' developments. Governmental regulators (e.g., space agencies and other government organizations) will need in-depth knowledge to systematically formulate and establish sufficiently adequate GNC requirements, standards, and best practices for such future autonomous systems. A full and comprehensive understanding of the way these novel autonomous GNC architectures need to be designed, verified, validated, and operated in a safe and reliable manner is not fully established on the complete space economy scale. While there has been some limited collaboration between industry and government organizations in this area, much more interaction would be beneficial for all parties. So, one can say that while the nontraditional New Space business paradigm offers benefits, it also poses GNC V&V concerns along a different dimension. While substantial accomplishments have already been achieved by applying the nontraditional time & cost-optimized approach to space systems development, there clearly remains considerable work to be performed and a deeper understanding of the overall risk/benefit trade to be had.

We must consider a future reality in which GNC systems will need to evolve from simply managing single vehicles towards the challenge of controlling multi-spacecraft cooperative systems with numbers that can range from a few (as in orbital servicing) up to thousands of spacecraft (in the case of dynamic adaptive constellations). Clearly these multi-vehicle systems will be required to provide autonomous collision avoidance functions and autonomous system reconfiguration capabilities in case of spacecraft-level failures. By their very nature, these future large-scale, hybrid perception and actuation decision systems will no doubt become more and more complex, representing greater GNC V&V challenges. As it stands today, our space GNC community of practice does not have well-established tools and methods to perform sufficient V&V on such large-scale systems.

These future missions may have a cadence of decision-making that exceeds communication constraints (e.g., time delays, data bandwidth, and limited communication windows). Therefore, time-critical decisions for performing orbit/trajectory control maneuvers, managing GNC system health, and/or performing GNC system reconfigurations may have to be made onboard the vehicle without human intervention.

As mission goals become more ambitious, exploration vehicles will likely fly in closer proximity to unexplored bodies and operate in uncertain, extreme environments that have unpredictable dynamic interactions with the vehicle. Operations that extend into unknown and uncharacterized flight regimes could pose unacceptable risks without GNC technological innovations, driving the near-term need for trusted, autonomous GNC. Examples are adaptive guidance for optimizing aerodynamic and/or propulsion performance during planetary entry, descent, and landing with precision, hazard-avoiding requirements.

Dealing with system complexity is a present and growing challenge for space agencies and their industry counterparts. The trend in GNC systems for future space platforms is likely to favor more complex implementations as mission requirements for autonomous operations become more demanding. Uncertainty and nonlinear dynamic coupling add to this complexity, potentially leading to a significant gap in the capability to perform the necessary prelaunch GNC V&V work. GNC algorithm complexity can be characterized by greater levels of system interactions and interdependencies within the various elements of the closed-loop system, including complex nonlinear coupled dynamic behaviors. Algorithm complexity will be driven by multiple types of system uncertainties as our space missions push into operational regimes with harsh, uncharacterized environments that can interact unpredictably with the spacecraft. Indeed, these conditions lead to more novel, and eventually more complex, GNC architectures with new functions that must be studied, understood, and ultimately, accepted by the engineering and regulating community.

System verification is a very resource-intensive phase of the mission life cycle. Consider that on a typical spacecraft project, a relatively small fraction of the total time is spent on actual design, while the majority of the time is used for planning and executing the V&V activities necessary to certify systems for flight readiness. There is a need for GNC V&V tool development and education to manage the risks of flying increasingly complex GNC systems. Likewise, there is a need to incorporate nontraditional GNC V&V tools to supplement those currently in use by industry.

The GNC V&V approaches and processes needed to address the next generation of complex GNC systems, which likely will employ various forms of modern GNC technology, are not currently established to the level the community will need in the future. While researchers and practitioners have made some progress in developing new GNC V&V methods for modern GNC systems, much work is needed to codify such methods in a comprehensive and systematic manner. While some emerging space organizations are incorporating advanced algorithms, part of the traditional GNC community is currently unprepared to efficiently perform the necessary GNC V&V functions to certify advanced GNC systems for safe and reliable flight. In addition, the forward-thinking R&D community has advanced the state-of-the-art in the area of GNC V&V for complex algorithms. New techniques will be needed to perform the necessary, and very challenging, V&V processes to flight-certify autonomous GNC functions.

Furthermore, current GNC V&V approaches are not well suited for advanced systems because linear gain and phase stability margins (which are the basis for most traditional stability and robustness requirements) do not hold for multivariable, uncertain, online, adaptable systems. Currently, there are no standard metrics that can be leveraged to define the requirement sets for such advanced systems. Recent metrics proposed and under development in the R&D community [e.g., robust regions of attractions, reachability, control barrier functions, set invariance (from control Lyapunov functions), contraction, and online monitors] hold promise for future applications.

One can envision a future in which the current GNC system architectures, which are almost entirely model-based and designed offline, will evolve into online, data-driven, decision-making systems with internal, adaptive, model-based architectures. This architectural evolution will be driven by increasingly demanding requirements to operate in highly uncertain, potentially unknown, extreme environments while performing maneuvers in flight regimes in which designers have little or no experience. Such futuristic architectures will essentially be online embedded learning systems. The modelling, design, and validation will be in situ and will evolve as the GNC system learns over time and/or over a number of flights. In this scenario the concept of “prelaunch” V&V varies, especially for the GNC systems on reusable launch vehicles. Advanced GNC systems of the kind envisioned here should have the capability to provide coverage for a wide set of missions, flight profiles, payloads, operational environments, etc. In other words, future GNC systems should be able, by design and self-evolution, to manage any combination of payloads and profiles without the need for GNC redesign. This is certainly a worthwhile goal, but that operational flexibility will come with a significant up-front, prelaunch V&V burden. In any case, for this futuristic vision to come about, a complete revision of the current GNC V&V process will be required given the revolutionary nature and architecture of self-learning adaptive GNC systems.

In the spirit of preparing for these future challenges, the Inter-Agency team has conducted preliminary investigations over the past 3 years into ways to advance the GNC V&V techniques that will be needed by future complex launch vehicles, spacecraft, and landers with autonomous GNC capabilities. This investigation identified several needs: educating the GNC workforce, developing new GNC V&V tools, and creating benchmark problems for the GNC community. This work and the first round of the seminar series talks culminated in an

Inter-Agency GNC V&V Workshop that was held virtually in April/May 2021. The results of this workshop are described in [Ref. 1].

There are gaps in our collective capabilities to successfully transition from traditional solutions to the mission-enabling advanced GNC system concepts and algorithms that will be needed in the near future. There is significant work to be done by space agencies, the R&D community, and space industry to be sufficiently prepared to infuse and verify the advanced, autonomous, nondeterministic GNC algorithms emerging from the R&D community. The remainder of this paper will present and discuss a series of proactive steps to be taken to meet the challenges and fill the gaps.

3. Near-Term Recommendations

In the near term, we see the benefit in pursuing two parallel paths to build momentum in the GNC community of practice. For one, organizations can identify advanced analysis tools and work to incorporate them into practicing GNC engineers' production workflows. Several such tools have already been identified [Ref. 1], but a concerted and intentional effort is needed to gain widespread traction.

As a second short-term action, benchmark problem(s) can be formulated and made available to the community to further stimulate the application of advanced algorithms and the use of the associated V&V tools amongst GNC practitioners. Three such benchmark problems are in development. Developing benchmarks is a necessary step but not sufficient on its own. The missing element to fully exploit and benefit from the benchmark problems is to create some form of community competition. To continue developing benchmark problems, an industry roundtable could be formed to generate problem(s) that address real, practical, short-term needs.

Ideally, the benchmark problem(s) require some advanced methods and tighter requirements, so that requirements cannot be met easily by using classical/existing methods. Those problems could then be fed to research teams as part of an organized competition model. Winners of the competition could earn the honors of presenting the solution as part of a prestigious international forum and lead or be involved with generating the next benchmark problem.

This competition model concept is similar to the widely successful Global Trajectory Optimization Competition (GTOC) model [Ref. 2]. GTOC started with a trajectory optimization problem presented to the international community. Teams worldwide compete to provide the best solution to the problem, typically generating new techniques and toolsets that are subsequently applied more broadly within the technical community. As an example, the NASA Marshall Space Flight Center's Space Launch System (SLS) trajectory design team developed new techniques to evaluate the SLS Block-1B design space by using techniques explored during a previous GTOC competition. Winning teams of each GTOC competition not only earn prestige, but also the opportunity to present their solution at an international forum and host the next competition.

4. Solution Strategy

This section discusses GNC V&V methods, tools, and processes and how they may apply to key stakeholders.

This strategy is based upon the desire to increase the awareness of the importance of the V&V process and the benefits of performing V&V as early in the design and development process as feasible for the most efficient problem resolution. Often this is not the case and most of the V&V process is deferred until the very late stages of the program or project with undesirable results. In this typical “kick the can down the road” scenario, design changes discovered by the V&V process occur in the latter stages of the system integration and test phase or worse, during system initial deployment. This is depicted in Figure 1, which is taken (and adapted) from a study of design change propagation and change management in the development of a complex large-scale sensor system [Ref 3]. Thus, our strategy encourages a project team to place a high value on the V&V process, embrace it, and embed it early in the design work to reap the advantages of resolving design issues very expeditiously. Employing modern model-based engineering techniques and innovative GNC verification methods/tools along with adopting a “Design-to-Test” philosophy can increase the awareness of design change needs and their impacts earlier in the GNC development cycle.

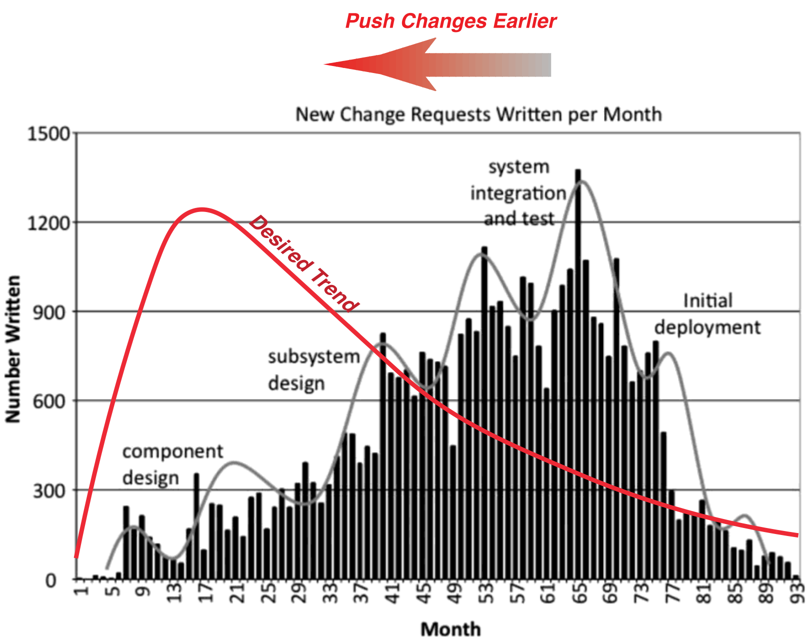

Figure 1. Change Requests Written Over Time (Number Written Per Month)
[Adapted from Ref. 3]

General Recommendations

Below are general recommendations followed by stakeholder-specific ones in subsequent sections:

- Emphasize the importance of V&V early in the project.

- Increase awareness and visibility of the criticality of GNC V&V in missions.
- Prioritize not only the development of new GNC algorithms, but also methods for validating these algorithms. Algorithm validation, and ideally mathematical proof, should be considered during GNC algorithm development.
- Develop benchmark problems to facilitate research.
- Use demonstrations of benchmark problems to disseminate new GNC V&V methods within the community.
- Encourage the quantification of the added value of novel solutions in terms of simulation time, development time, cost, reusability, and accuracy.
- Develop training and education programs to enhance cross-disciplinary thinking and knowledge in the workforce.

Recommendations for Academia and Research Organizations

Research organizations are involved in developing new GNC algorithms, technologies, and analysis methods, often in the early phases of development or as basic research. Recommendations to research organizations in the context of GNC algorithm V&V are:

- Prioritize not only the development of new design/analysis algorithms, but also methods for validating these algorithms. We suggest that algorithm V&V, ideally including mathematical proof, should be considered during the GNC design/analysis algorithm development phase.
- Research on algorithm V&V tools and methods development should be regarded as a bone fide innovative topic and should encourage post-doctorate research. Such methods and tools are needed to perform V&V early in the design cycle and gain trust in increasingly complex GNC algorithms.
- Ensure there is an in-depth understanding of the industrial GNC V&V practices and their applications of GNC V&V tools and methods. This is needed to serve as a basis for the development of advanced V&V tools and methods most likely to be relevant to and prove useful in an industrial production environment.
- Utilize the available benchmark problems to focus GNC V&V research efforts.
- Formulate a curriculum on complexity management and GNC systems verification engineering to educate the workforce on algorithm V&V, limitations of classical tools, alternate options available, and research needed to fill gaps.
- Develop a multi-disciplinary learning R&D ecosystem that includes cross-disciplinary interactions, case studies, research topics, and seminars. Collaboration between different disciplines, departments, and facilities is recommended to support the development of new V&V tools and methods. This collaboration would potentially include the GNC, artificial intelligence/machine learning, optimization, modeling and simulation, and software disciplines.

- Investigate GNC V&V tools and methods that can address not only the closed-loop system-of-interest, but also critically assess and provide insights into the control system's overall architecture.
- Identify and investigate areas where machine-learning based tools and methods could directly address GNC V&V challenges.
- Quantify the added value of novel GNC V&V techniques as part of the documentation and presentation process, potentially including discussion of simulation time, development time, cost, and accuracy.

Recommendations for Industry

Industry stakeholders are responsible for the development, manufacturing, and testing of space products and space vehicles. Recommendations to industry in the context of GNC algorithm V&V are:

- Prioritize the ability to perform GNC V&V early in the design cycle when the GNC algorithms and architecture are being formulated.
- Formulate clear strategies that are tailored for individual categories of space missions, such as high-reliability flagship-class missions, agile missions, and time & cost-optimized missions. Establish risk mitigation approaches in all cases, but work to fully understand and control, when necessary, any risk factors associated with reduced GNC V&V efforts and the use of COTS parts/components.
- Contribute to the identification of strengths and weaknesses of current GNC V&V tools, methods, and processes through practical use and real-world experience.
- Report user feedback to the initiating/funding space agency, tool vendors, and/or algorithm originator.
- Continuously educate the workforce on the applicability and limitations of the existing and the newly emerging GNC design/analysis techniques, along with their associated V&V tools and methods.
- Foster on-the-job training and practical experience in performing the various steps of the V&V process.
- Quantify the added value of novel GNC V&V solutions that have been adopted in terms of simulation time, development time, cost, reusability, accuracy, etc.
- Keep up to date with new methods, tools, and processes to increase long-term competitiveness.

Recommendations for Space Agencies

Space agencies are often in a unique position and ideally suited to bridge the gap between research organizations and industry counterparts. Additionally, the GNC field is well-positioned to lead a cultural change towards cross-disciplinary collaboration and development of relevant V&V solutions, as most issues arise at the intersection of different disciplines. Recommendations to space agencies in the context of GNC algorithm V&V are:

- Advocate for pilot projects that promote the generation of novel solutions to industry GNC V&V challenges. For example, where appropriate, experiment with machine-learning based approaches for performing GNC V&V.
- Begin the process of elaborating on and formulating GNC design requirements and associated GNC V&V requirements, along with associated metrics and verification means and facilities, for future autonomous GNC systems. Defining at least a notional set of such requirements would potentially provide a framework to support/motivate the development of new GNC V&V techniques.
- Investigate and document to what extent the classical stability and performance metrics are appropriate for the new types of GNC systems. This body of foundational work should illustrate the limits of validity or demonstrate their invalidity in certain cases through counter-examples. This work should be coupled with proposing alternative GNC metrics (and associated verification methods) to adequately specify stability and performance as needed by the new space missions.
- Collect industry experience and provide feedback to research organizations.
- Provide demonstrations of new GNC V&V solutions and quantification of benefits to showcase the added value to industry.
- Advocate for demonstration missions that will build confidence and reduce risk associated with advanced GNC algorithms and corresponding V&V solutions.
- Develop a comprehensive portfolio of GNC V&V tools and processes that are mapped to individual categories of space missions and phases.
- Implement training and educational programs to enhance cross-disciplinary thinking and knowledge of V&V tools and methods in the workforce.
- Increase awareness and visibility of the criticality of GNC V&V in all classes of missions.
- Avoid postponing GNC V&V to later phases of a project, when fixing issues becomes more expensive.
- Provide documentation with guidelines and best practices for GNC V&V processes.
- Implement and enable the use of facilities for end-to-end GNC V&V testing.
- Support emerging industries (New Space) in the consolidation of their GNC V&V strategy.
- Document and maintain records of lessons learned and success stories from industry adoption of new solutions.
- Support the transition of solutions from academia to industry via tool vendors, including moderation, management, support, and funding.

- Fund and foster the development of nonlinear tools (e.g., Lyapunov, describing functions, and other forms of limit cycle analysis) to supplement traditional analyses (e.g., Monte Carlo simulations).
- Develop and widely share challenging benchmark problems to facilitate research of advanced GNC algorithms and associated V&V solutions.
- Incorporate in-orbit results and data into future developments, as much as possible, in accordance with proper Intellectual Property management.
- Facilitate knowledge transfer and dissemination of newly emerging algorithm V&V tools, methods, and techniques through familiarization meetings, training sessions, technical workshops, seminar series, handbooks, and guidelines/standards documents.
- Require development and implementation of V&V plans early in the project life cycle.

Recommendations for Tool Vendors

Tool vendors provide software and hardware solutions that can be used for GNC algorithm V&V. Recommendations to tool vendors in the context of GNC algorithm V&V are:

- Provide validated tools that implement novel V&V techniques to promote adoption across the GNC community of practice. This process could be accelerated with rapid prototyping of newly emerging GNC V&V tools, in collaboration with industry, to determine relevance and utility in the industrial production environment.
- Pay attention to the value proposition of purchasing/licensing tools along with providing support services such that industry users obtain the best value. For example, training and detailed engineering support could be included in the vendor's tool offerings.
- Incorporate data-driven, model-based, and machine-learning engineering methods into the GNC algorithm V&V toolsets.
- Encourage a high degree of automation in the GNC V&V tools to increase efficiency.
- Provide periodic quantitative feedback to the GNC user community on the comparison between performance of different tools to highlight their limitations, constraints, strengths, and weaknesses. This type of feedback would be especially informative in the context of applying the tools to established benchmark problems.
- Provide explicit quantification of the added value of novel tools.
- Ensure interoperability of toolsets across disciplines.

5. Conclusions

We live in a time with many disruptive innovations dramatically changing the landscape of our world. Technologists and engineers within the GNC discipline are certainly contributing to these innovation-driven changes, and there will be much more to come. As a community, we have a rich tradition of success, and one can easily speculate that new GNC innovations will become central to future technological advances in space transportation and space exploration, along with their widespread application in the management and control of autonomous aeronautical vehicles. These future GNC innovations will be consistent with the history of our discipline and ubiquitous, yet paradoxically hidden from plain sight due to their highly embedded nature. Innovations in GNC should figure prominently in applications where capabilities for perception, estimation, optimization, and autonomous decision-making in an uncertain environment are at a premium.

However, this community cannot depend on continuing to leverage the successes of our past to carry us forward. If we truly believe in a future that will trend towards increasingly complex, fully autonomous, online, and adaptive GNC systems for future space missions, then the community needs to have an increased awareness of the inherent challenges and needs to start responding in a coordinated manner across all segments of our community. The point of this paper is to emphasize the need for our community to act now to develop the necessary GNC V&V tools, methods, and techniques to meet the coming challenges in order to prepare for the implementation of entirely new classes of autonomous GNC systems.

Motivation for the work summarized in this paper came from concerns about the expected growth in complexity of future autonomous GNC systems. To this end, the Inter-Agency Working Group has conducted preliminary investigations into advancing GNC V&V techniques, which resulted in the identification of the need for, among other things, education, new V&V tools, and benchmark problems for the GNC community. Additional motivation comes from the awareness that the V&V phase of a mission can become the costliest part of mission development, especially if performed late in the life cycle.

It is the conclusion of our Inter-Agency Working Group that the GNC V&V approaches and processes needed to address the next generation of complex GNC systems, which likely will employ various forms of modern GNC technology, are currently not fully established to the level the community will need in the future. While researchers and practitioners have made some progress in developing new GNC V&V methods for modern GNC systems, much work remains to be done to codify such methods in a comprehensive and systematic manner.

Meeting these needs will first require an increased awareness of the issues across the community. Changes in awareness should lead to constructive changes in the way we think about our discipline and its future in the context of capabilities for the V&V of advanced GNC systems. Real breakthroughs will come with new perspectives, priorities, and strategies, along with the novel and relevant GNC V&V-focused technological innovations that will be needed. The time to act is now. This paper is a call to action, and it recommends some proactive steps for individual elements of the GNC community of practice to meet the challenges of and fill the gaps in GNC V&V for the future.

> *ELECTRIC LIGHT DID NOT COME FROM THE CONTINUOUS IMPROVEMENT OF CANDLES*
>
> *Attributed to Professor Oren Harari*

6. Contributing Members of the GNC V&V Working Group

Members of the Inter-Agency GNC V&V Working Group who contributed to this paper are listed below. For a full, current list of the Working Group members please visit the site: https://indico.esa.int/event/350/page/513-organising-committee.


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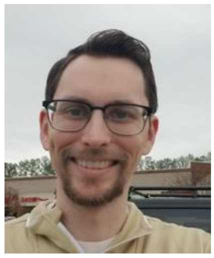
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