V&V Challenges for Modern GNC Systems

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Inter-Agency GNC V&V Working Group

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Abstract for Today's Talk

Future space systems will heavily 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. Our current GNC systems are already highly automated and complex. The trend is for missions to become more ambitious, thus the expectation is that the GNC systems for launch vehicles and space platforms will require even higher levels of performance and autonomous operation than previously encountered. Many future missions will have demanding new requirements for onboard autonomy, resiliency, reconfigurability, performance optimization, adaptation, and fault-tolerant operations. An Inter-Agency GNC V&V Working Group has been investigating the advanced technologies, approaches, methodologies, tools, and processes that will be needed to efficiently perform the necessary V&V to ensure reliable and safe flight GNC system operation. Efficiency is critically important as it is well known that V&V is a cost driver in GNC system development process. In this ADCSS talk the findings and recommendations of the Inter-Agency GNC V&V Working Group will be summarized. The recent development of relevant benchmark problems will also be discussed. The benchmark problems are seen as a means to help bridge the gap between research organizations and industry counterparts, especially in the area of developing the new GNC V&V technologies. Lastly, the plans for a GNC V&V Workshop in July 2025 will be highlighted for the community. The purpose of this Workshop will be to identify and discuss the challenges and solutions for the new types of GNC V&V technologies, approaches, methodologies, tools, and processes needed to address the next generation of GNC systems for demanding aerospace mission applications. As will be discussed the primary Workshop objectives will be to raise awareness about GNC V&V challenges/issues within our community and to provide a forum for collaborative information sharing/learning on the topic of GNC V&V for future systems.

"This really is an innovative approach, but I'm afraid we can't consider it. It's never been done before."

Presentation Outline

➢ **Presentation Objectives**

➢ **Timeline of Inter-Agency GNC V&V Working Group (WG) Activities**

➢ **Who are the members of the Inter-Agency GNC V&V WG**

➢ **Motivation: Why the focus on GNC V&V?**

➢ **Some Findings and Recommendations the of Inter-Agency GNC V&V WG**

➢ **NASA Benchmark Problem overview**

➢ **Inter-Agency GN&C V&V Seminar Series**

➢ **Plans for a 2ⁿᵈ GNC V&V Workshop in July 2025 in Toulouse, France**

➢ **Survey and Discussion on GNC V&V with ADCSS Audience**

Presentation Objectives

- ➢ **Introduce the ADCSS audience to who the Inter-Agency GNC V&V Working Group is and what we have been doing**

- ➢ **Briefly review highlights of the recent Inter-Agency GNC V&V summary paper entitled *"Looking to the Future: A Call to Action for Advanced GNC Algorithm Verification and Validation"***

- ➢ **Obtain feedback from the ADCSS audience regarding their views on GNC V&V challenges and opportunities**
  - ➢ **The Working Group is very interested in collaborative interaction with the community on this important topic**

Timeline of Inter-Agency GNC V&V WG Activities

➢ ESA/NASA initial engagement (September 2018): Started down a path towards holding an ESA/NASA Control Systems Workshop

➢ Changed direction in 2019: narrowed focus of ESA/NASA **collaboration** to GNC Verification & Validation

➢ Formed a broader Inter-Agency **collaboration** by including CNES, DLR, ONERA, and Institut Supérieur de l'Aéronautique et de l'Espace (ISAE-SUPAERO), and more recently, Agenzia Spaziale Italiana (ASI)

➢ GNC V&V Seminar Series started in September 2020 – **52 seminar talks to date with 569 individuals in the registered seminar audience.**

➢ 1st (Virtual) Workshop hosted by Inter-Agency WG was held in April/May 2021 – total of **30 presentations given in 8 separate sessions**

➢ **Presented AAS GNC Conference paper on results from 1st (Virtual) GNC V&V Workshop** (February 2022)

➢ 1st Working Group Face-to-Face (F2F) meeting at ESA ESTEC (December 2022)

➢ Held **GNC V&V Special Session at ESA International GN&C Conference** in Sopot, Poland (June 2023)

➢ **Recently completed Inter-Agency GNC V&V summary paper entitled *"Looking to the Future: A Call to Action for Advanced GNC Algorithm Verification and Validation"***

➢ 2nd Working Group F2F meeting at ESA ESTEC (June 2024)

➢ **Planning a 2nd GNC V&V Workshop: 9-10 July 2025 in Toulouse –Call for Abstracts is already out**
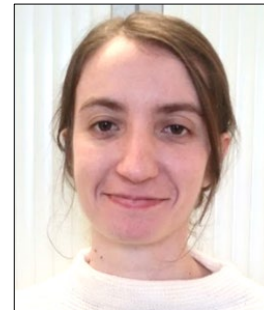
Inter-Agency GNC V&V Working Group Members
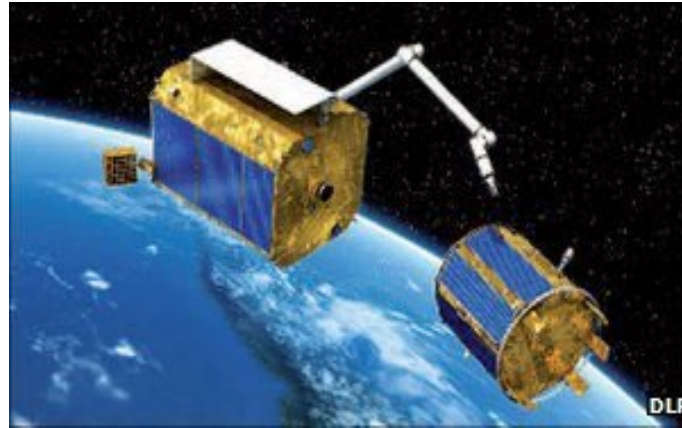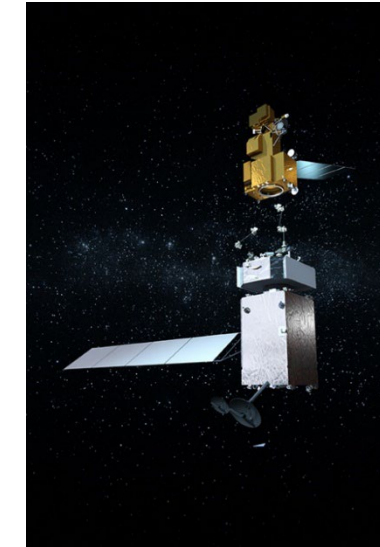
Envisioned Future NASA and ESA Missions Will Drive the Need for Higher Performance & Trusted GN&C Autonomy

Small Body Entry, Descent, and Landing

Servicing Space Tug (ESA)

In-orbit Service, Assembly, and Manufacturing (NASA)

Europa Undersea Cryobot

Comet Sample Return

Dragonfly Robotic Rotorcraft

➢ Increasing levels of autonomy drives **<u>complexity</u>** in modern aerospace systems.
➢ Performance/Robustness tradeoff becoming more and more demanding.
➢ New Space ecosystem: driven by lower cost & faster development.

Motivation

- ➢ **The major motivations of the Working Group are to:**

  - ➢ Establish a common understanding within the community of modern GNC design synthesis tools and methods

  - ➢ Establish a common understanding of existing V&V tools

  - ➢ Define needs for the next-generation of V&V tools for increasingly complex GNC space systems.using modern methods

  - ➢ **Serve as a bridge between the R&D researchers and the industrial practitioners (who need efficient GNC V&V methods and tools)**

    Note: Our focus was on algorithms not aspects such as HITL V&V Testbeds

Quantify the gap in V&V tools for increasingly autonomous/complex/high performance/efficient GNC systems

Why the Focus on V&V?

➢ **Considerable resources are invested in V&V. Likely this trend will only grow as GNC complexity increases**

➢ **A "Kick the Can Down the Road" mentality with V&V is not uncommon on projects allowing issues to accumulate**

➢ **Need to prepare community for preforming sufficient V&V to certify safety-critical systems that will use advanced/modern GN&C methods**

  ➢ What does future V&V look like for adaptive flight control, real-time trajectory optimization, and/or systems exploiting Machine Learning ?
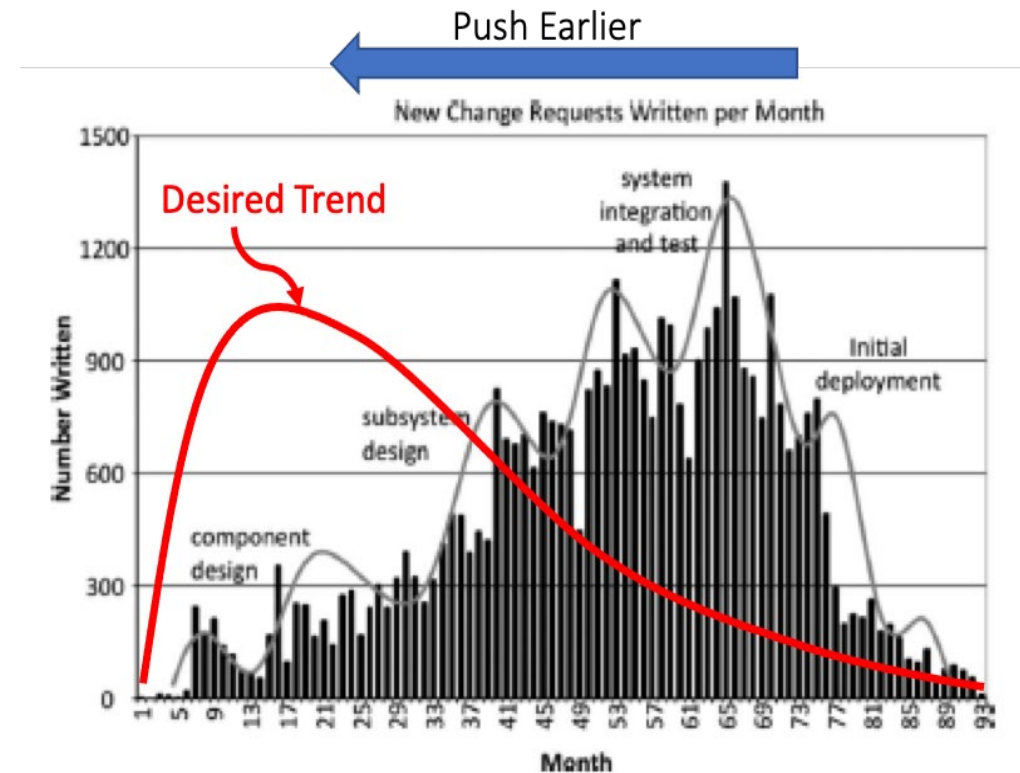
Virtual GNC V&V Workshop (April/May 2021)

VERIFICATION AND VALIDATION (V&V) OF GUIDANCE & CONTROL SYSTEMS: RESULTS FROM THE FIRST INTER-AGENCY WORKSHOP ON GNC V&V

Cornelius Dennehy,[*] Samir Bennani,[†] Uday Shankar,[‡]
Jeroen Vandersteen,[§] Tannen VanZwieten,[**] Paul Von der Porten,[††]
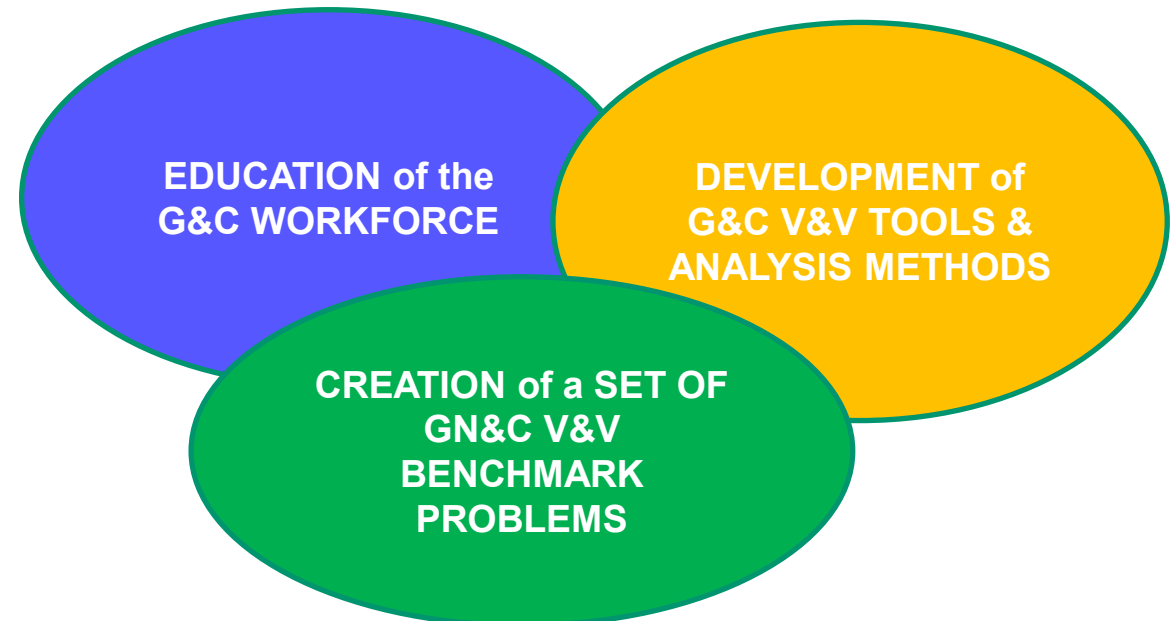Aron Wolf,[‡‡] Bénédicte Girouart,[§§] and Massimo Casasco[***]

Guidance, navigation, and control (GNC) of aerospace systems is growing more complex. Current verification and validation (V&V) approaches and processes are not adequate to cope with the evolving GNC architectures and topologies being driven by autonomy. To address this, several space agencies (NASA, ESA, DLR, CNES) and the French research center ONERA sponsored a series of seminars and a workshop, presented from fall 2020 to spring 2021. To mobilize the GNC workforce, this white paper summarizes the workshop outcomes, identifies available tools and existing gaps in V&V capability, and suggests a prioritization of tool and method development needs for V&V of advanced GNC algorithms. Several major emerging themes were recognized and examined: state-of-the-art tools being developed mostly in academic research settings; education and awareness within the GNC work force, creating opportunities to address the most urgent V&V gaps; increasingly autonomous systems that still require assurance; formal software verification that has progressed enough to apply to online flight software; NASA's advances in V&V and certification for airplanes—processes that can be a roadmap for spacecraft applications; and short-term needs for the formulation and release of relevant V&V benchmark problems as a practical way forward. The opportunities provided by the joint resolution of specific V&V benchmark problems can help close the development gap between academia and industry while gradually tightening the awareness gap. This provides a good basis for further discussions with the goal of converging to a consensus white paper for GNC V&V.

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This AAS paper (22-055) summarizes the workshop proceedings, including:

(1) suggested workforce education areas based on availability of advanced tools;
(2) description of existing gaps in V&V capability and open areas of research for GNC V&V tools, including methods to fill these gaps; and
(3) identification of benchmark problems.

### THREE MAJOR THEMES EMERGED FROM April/May 2021 Virtual GN&C V&V Workshop

EDUCATION of the G&C WORKFORCE

DEVELOPMENT of G&C V&V TOOLS & ANALYSIS METHODS

CREATION of a SET OF GN&C V&V BENCHMARK PROBLEMS

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

Looking to the Future:

A Call to Action for Advanced GNC Algorithm Verification and Validation

8 February 2024

Version 1.0
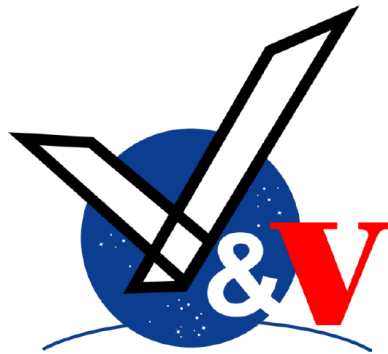
Prepared by:
The Inter-Agency Guidance, Navigation, and Control
Verification and Validation Working Group (GNC V&V WG)

➤ The WG focus has primarily been on addressing the GN&C V&V challenges that arise as drivers for more autonomy appear and system complexity increases.

➤ Purpose of this document was to **capture the findings and recommendations of the WG** and to lay out future directions (i.e., a vision for the future) for Agency investments in V&V methods and tools for the most promising advanced GN&C algorithms

➤ Written as common Inter-Agency technical position paper **intended to inform and influence organizational decision makers**.

➤ This document is publicly available at:

https://ntrs.nasa.gov/citations/20240003178

we will also place this paper on our ESA Indigo website

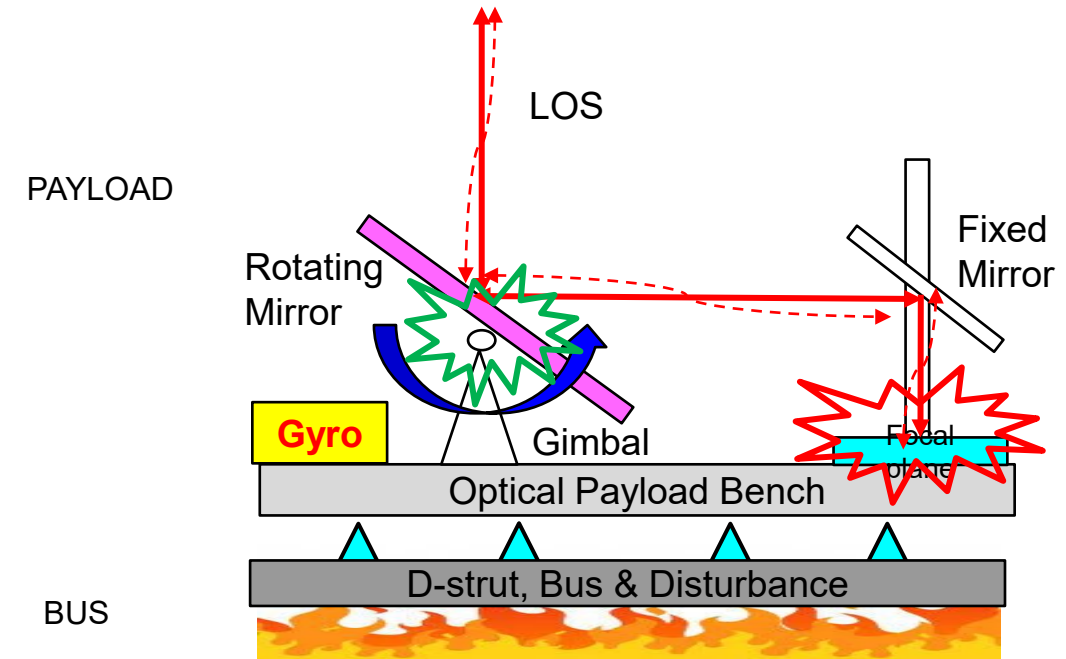# General Recommendations from the GNC V&V WG Summary Paper

➢ Emphasize the **importance of V&V early** in the project life cycle.

➢ 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 design methods <u>and</u> 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.

NASA's Space Observatory Precision Pointing Benchmark Problem

- ➢ **NASA, in collaboration with The Aerospace Corporation, has formulated a new space observatory benchmark problem focused on the challenging aspects of optical payload Line-of-Sight (LOS) precision pointing.**

- ➢ **New benchmark problem provides common framework for researchers to investigate various advanced control techniques that the aerospace industrial community has been hesitant to employ due to a perception of higher risk and/or unfamiliarity.**

- ➢ **Benchmark problem could have a significant influence on the field by providing an opportunity for users to experiment with solutions based on neural networks, H_∞, adaptive methods, machine learning, model predictive control, on-line convex optimization, and other modern, novel, and evolving techniques. <u>Complete solution will include V&V.</u>**

- ➢ **Academic researchers are familiar with these advanced control techniques, unfortunately many do not have access to recognized high-fidelity benchmark problems.**

- ➢ **This benchmark problem therefore can serve as a bridge between the academic and industrial communities.**

- ➢ **Currently in process of obtaining approval for public release from the NASA Software Release System (SRS).**

PAYLOAD

LOS

Rotating Mirror

Fixed Mirror

Gyro

Gimbal

Focal plane

Optical Payload Bench

BUS

D-strut, Bus & Disturbance

This new benchmark is intended to facilitate infusion of new control approaches (<u>along with their V&V methods)</u> from the academic R&D world to the industrial production environment.

Inter-Agency GN&C V&V Seminar Series

➢ Purpose is to identify and **discuss key open research questions in advanced G&C algorithms and the associated V&V methods** at the intersection of Academia/Industries/Agencies. Identify the State-of-the-Art algorithms and V&V methods/tools/techniques

➢ Used technical content of seminar series talks to help the Working Group to sharpen the scope and content of Virtual GN&C V&V Workshop in 2021

➢ Our seminar series has been held approximately once per month since 2019. Have had 52 seminar talks to date (all recorded and online) with 569 individuals in the registered seminar audience which is good mix between academia, industry and agencies.

➢ Presentations are typically 1 hour, with some time for Q&A; and typically held on one Thursday per month at 11am Eastern/5pm CET.

➢ More information and recordings from previous seminars can be found on the ESA Indico site at: https://indico.esa.int/e/GNC_VnV_seminar_series

➢ Two last points: 1) Please **register (for free ☺) on the ESA Indico site** using link above and 2) we are **always looking for seminar speakers** (so volunteer yourself or a colleague).

SAVE THE DATE
2ⁿᵈ Inter-Agency GN&C V&V Workshop
9-10 July 2025 in Toulouse, France

TOPICS OF INTEREST:

Bridging the Research-Industrial Gap

Efficient V&V Tools and Methodologies

V&V Research in Academia

GNC Benchmark Problems and Potential Solutions

Recent Real-World Space Mission GNC V&V experiences

New Space Alternative Approaches to the Traditional GNC V&V

Innovative Student Research in GNC V&V (Poster Session)

V&V Methods and Techniques for Non-Space Safety-Critical Mission Applications

Call for Abstracts has been issued. See Workshop website. Abstracts due by 6 December.

HANDS-ON DYNAMIC SYSTEM MODELING and VERIFICATION TUTORIALS ALSO OFFERED by ISAE-SUPAERO & ONERA 7-8 JULY 2025

Workshop Website: https://events.isae-supaero.fr/e/VVworkshop2025

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GNC V&V Workshop Objectives & Structure

1) **Raise awareness about GNC V&V challenges and issues within our community**

2) **Provide an informal interactive forum for knowledge sharing and learning on the topic of advancing GNC V&V to meet future challenges.**

This Workshop will not be structured as a typical conference. Abstracts are being solicited for brief talks only, not full technical papers. Envisioned to be an informal forum conducive to group technical interactions.

Parting Thought

ELECTRIC LIGHT DID NOT COME FROM THE CONTINUOUS IMPROVEMENT OF CANDLES

Attributed to Professor Oren Harari

Survey Questions (1-6)

Survey QR Code

1) My current professional role is?

2) I am well aware of the activities of the Inter-Agency GNC V&V Working Group?

3) I have seen the Working Group's summary paper "Looking to the Future: A Call to Action for Advanced GNC Algorithm Verification and Validation"?

4) The GNC V&V process is recognized as a significant challenge area by my organization?

5) The GNC V&V process used within my organization consumes significant project resources?

6) There is a critical need to emphasize the importance of GNC V&V early in a project life cycle?

Survey Link: https://docs.google.com/forms/d/1CLV56pGlFD7EKPGr3ttgoY9Yum9UQrqjLffzIyCyEns

Survey Questions (7- 12)

7) My organization has seen a challenging increase in system complexity due to demanding mission requirements for onboard autonomy, resiliency, reconfigurability, performance optimization, adaptation, and fault-tolerant operations?

8) My organization would benefit from a better understanding of next-generation GNC V&V tools that address the issues posed by increasingly complex GNC space systems?

9) My organization is developing advanced technologies, approaches, methodologies, tools, and/or processes needed to efficiently perform the necessary V&V to ensure reliable and safe flight GNC system operation?

10) I would be interested in developing a solution to a Space Agency-provided benchmark problem?

11) I would be interested in tutorial training and educational programs to enhance my cross-disciplinary thinking and knowledge related to GNC V&V?

12) I would be interested in collaborating with the Inter-Agency GNC V&V Working Group?

THANKS FOR YOUR ATTENTION!

QUESTIONS?

COMMENTS?

YOUR THOUGHTS ON GNC V&V CHALLENGES?

BACKUP CHARTS

Airbus-led Study on "New AOCS/GNC Technologies for Industrial Efficiency"

Airbus's view of today's As-is-State (from their paper):

➢ Increased cost pressure despite increase of satellite system complexity => Risk
➢ AOCS/GNC V&V is a cost driver
➢ Increasing gap between leading-edge ("new") V&V technologies developed at research institutes and V&V performed by industry
➢ Need of technology/tools enhancement for real mission applications
  ➢ Kicking off a follow-on activity with CDR-level benchmarks
    1. Plant modelling, LFT (SDTlib)
    2. Sensitivity, worst case and probabilistic robustness
      ➢ LFT-based (STOWAT, SMART, GSST)
      ➢ Sampling of the uncertainty space (STAMP)
    3. Optimization framework (OPTI)

Airbus Motivation and Goal:

➢ Enabling complex future systems avoiding cost explosions
  ➢ Industrial Efficiency

Breckenridge 2024

DE-RISK NEW AOCS/GNC V&V TECHNOLOGIES FOR INDUSTRIAL EFFICIENCY

Stefan Winkler,[*] Maurice Martin,[†] Ramin Geshnizjani,[‡] Harald Pfifer,[§] Felix Biertümpfel,[**] Lisa Hafemeister,[††] and Emilie Pelletier[‡‡]

Cost pressure in space industry calls for challenging established tools and processes. New technologies are often promoted as solution by their developers and some spacecraft customer. With the study underlying this paper Airbus accepts the challenge. The study de-risks a subsequent bigger activity by testing and selecting the most promising technologies for verification and validation of the AOCS/GNC system of real missions. The technologies are applied to mission benchmarks covering linear and nonlinear control loops. In focus are uncertain spacecraft modelling, sensitivity and robustness analysis using μ-, sample- and optimization-based technologies for standard and probabilistic robustness (stability, performance). In conclusion, the presented selected technologies shall be enhanced in the follow-on study to handle hybrid multi-rate control loops to be fully applicable to real-world mission needs.

INTRODUCTION

Two industrial motivations for research and development studies can be distinguished: (1) solving a problem that has not been solved before, (2) solving a problem that has been solved before but in a more efficient way. While enabling technology, (1), enjoys great appeal among (employed) engineers, (2) is often rated as less attractive. Here we focus on (2).[1] And we de-risk a subsequent bigger study by hands-on testing and selecting new verification and validation (V&V) technologies for attitude and orbit control / guidance navigation and control systems (AOCS/GNC) for their applicability in industrial spacecraft development. We aim at bridging the gap between the state-of-the-art defined by research institutes and the day-to-day work environment at established large spacecraft industry for the benefit of both research and industry.

The work is motivated by the steady increase of cost pressure in industry despite a steady increase of spacecraft system complexity and needs.[2] This bears the risk of cost explosion in future missions if not counteracted early enough. V&V activities constitute a significant part of the overall AOCS/GNC system development costs. This large proportion justifies "V&V" as being in the focus. It is, however, just one element to increase efficiency of the overall spacecraft devel-

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More Recommendations from the GNC V&V WG Summary Paper

A Few Key Recommendations for Space Agencies

Consider that the 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.

1) Investigate and document to what extent the classical stability and performance metrics are appropriate for the new types of GNC systems. 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.

2) Collect industry experience and provide feedback to research organizations.

3) Provide demonstrations of new GNC V&V solutions and quantification of benefits to showcase the added value to industry.

Key Themes from Seminars and the Virtual Workshop

- **Classical verification methods are insufficient**

  - Gain and phase margins are inadequate

  - Classical Monte Carlo methods cannot identify conditions leading to failure

- **Robust control theory provides techniques that can be used for V&V of nonlinear systems**

  - Disk margins ☞ Sector-bound nonlinearities ☞ LMIs ☞ deterministic μ-analysis ☞ LFTs ☞ IQCs

  - Optimization-driven Monte Carlo techniques

  - Probabilistic μ-analysis – combine frequency and time domain techniques

  - Requirements could be embedded in the model itself for analysis and design

- **Potentially there are valuable lessons for space systems from autonomous aircraft certification process.**

  - Robust control methods, uncertainty quantification, etc.

Objectives of the GN&C V&V Seminar Series and Associated Virtual Workshop

1) Identify and discuss key open research questions in advanced G&C algorithm V&V at the intersection of Academia/Industries/Agencies. Identify the State-of-the-Art algorithms, tools and techniques

2) Use technical content of seminar series talks to help the Workshop planning committee sharpen scope of actual Workshop in 2021

3) Develop an **Inter-Agency White Paper** laying out future directions (a vision for the future) for Agency investments in V&V methods and tools for the most promising advanced GN&C algorithms.

Themes from Seminars and the Virtual Workshop (Continued)

- **Need for integrated understanding of pointing error metrics**

  - Multidisciplinary/multi-physics and formalized approach needed

- **Autonomous systems and assurances**

  - Without assurances, there is no useful autonomy

  - Assurances need formal software methods

- **Continue to develop and scale new methods, e.g.:**

  - Formal verification of control system software

  - Domain-specific languages

  - Signal temporal logic for event-based constraints

  - Multi-physics modeling of spacecraft system dynamics

  - Fast software, e.g., Julia ☞ Modia

- **Develop benchmark problems for community use**

Major Findings from the Workshop

1. Advanced and newer methods and software are being developed or adapted from other disciplines

2. Industry is still using conventional tools, creating a knowledge gap

   • Need to bridge gap between industry and researchers

3. Systems requirements and specifications should be embedded upfront in the models

   • Models will contain physics, requirements, and uncertainties formalized in a math language

   • Can provide assurances for autonomous systems (no autonomy without assurances)

4. These need to be formalized via certification of robustness

   • Agencies need to develop roadmaps and standards

5. Finally, need benchmark problems to support community development of advanced solutions and associated V&V methods

Recommendations from Workshop

1. **Formulate** a curriculum in complexity management to inform current and future practitioners

    - See: IEEE CSS *Control for Societal-Scale Challenges: Roadmap 2030*

2. Clearly **articulate** benefits of new methods and tools, but also their limitations and underlying assumptions

3. Foster the use of new <u>formal</u> analytical and software tools

4. **Prepare** the GNC community to understand and prepare for ongoing trends

5. **Adopt** a "**formal digital systems** engineer POV" and "**complexity management**"

6. **Encourage** interdisciplinary communication and vertical integration

7. Government agencies should use these results to **develop strategic** roadmaps

8. Continue to **develop** benchmarks to illustrate how these methods work