Present Challenges, Critical Needs, and Future Technological Directions for NASA's GN&C Engineering Discipline

Cornelius J. Dennehy[1]
NASA Engineering and Safety Center (NESC)

The National Aeronautics and Space Administration (NASA) is currently undergoing a substantial redirection. Notable among the changes occurring within NASA is the stated emphasis on technology development, integration, and demonstration. These new changes within the Agency should have a positive impact on the GN&C discipline given the potential for sizeable investments for technology development and in-space demonstrations of both Autonomous Rendezvous & Docking (AR&D) systems and Autonomous Precision Landing (APL) systems. In this paper the NASA Technical Fellow for Guidance, Navigation and Control (GN&C) provides a summary of the present technical challenges, critical needs, and future technological directions for NASA's GN&C engineering discipline. A brief overview of the changes occurring within NASA that are driving a renewed emphasis on technology development will be presented as background. The potential benefits of the planned GN&C technology developments will be highlighted. This paper will provide a GN&C State-of-the-Discipline assessment. The discipline's readiness to support the goals & objectives of each of the four NASA Mission Directorates is evaluated and the technical challenges and barriers currently faced by the discipline are summarized. This paper will also discuss the need for sustained investments to sufficiently mature the several classes of GN&C technologies required to implement NASA crewed exploration and robotic science missions.

Nomenclature

ACS	=	Attitude Control Subsystem
AR&D	=	Autonomous Rendezvous and Landing
CoP	=	Community of Practice
DDT&E	=	Design, Development, Test and Evaluation
DoD	=	Department of Defense
EDL	=	Entry, Descent and Landing
ERV	=	Emergency Rescue Vehicle
FPA	=	Focal Plane Array
GN&C	=	Guidance, Navigation, and Control
ISS	=	International Space Station
LEO	=	Low Earth Orbit
NASA	=	National Aeronautics and Space Administration
NEO	=	Near Earth Object
NESC	=	NASA Engineering and Safety Center
NRC	=	National Research Council
OML	=	Outer Mold Line
PRP	=	Precursor Robotic Program
R&D	=	Research and Development
ROIC	=	Read-Out Integrated Circuits
SPT	=	Space Technology Program

[1] NASA Technical Fellow for GN&C, NASA Goddard Space Flight Center, Mail Code 590, Greenbelt, MD 20711, USA, 240-687-9077, cornelius.j.dennehy@nasa.gov, Member AIAA

TDT	=	Technical Discipline Team
US	=	United States

I. Introduction

NASA is currently undergoing significant changes and a substantial redirection. The Agency is in the process of shifting its approach for Human Exploration and is exploring the 'Flexible Path' strategy to extend human presence beyond Low Earth Orbit (LEO). Several new programs that seek to foster a sustainable human space exploration enterprise are also being formulated. At the same time there is significant uncertainty in the future of the Constellation Program as it is being restructured; for example, a modified Orion spacecraft development may continue in the form of an Emergency Rescue Vehicle (ERV). Plans are being made for the extension of the International Space Station (ISS) to at least 2020. Commercial approaches to deliver both cargo and crew to the ISS in LEO are being formulated. All this is happening at the same time the Space Shuttle Program is anticipated to come to an end in 2011. NASA has formed multiple study teams to investigate various implementation options for taking the Agency in these new directions, if and when authorized by Congress. Although the Agency's philosophy and approach to exploration will apparently change, NASA's fundamental human spaceflight goal remains the same: to send human explorers into the solar system to stay.

Notable among the changes occurring within NASA is the stated emphasis on technology development for more economical and sustainable exploration. Technology development plans and integration across mission directorates is currently being formulated. One particular aspect of NASA's new Human Exploration strategy is the significant focus on technology development to reposition NASA on the cutting-edge by the creation of a new DARPA[2]-like Space Technology Program (STP). Some estimates indicate the new STP will potentially be funded at levels sufficient enough (e.g., $5B over 5 years) to significantly push new space system technological developments in a focused and integrated manner. A guiding principle in the technology developments will be an increased emphasis on partnerships with other government agencies, national laboratories, not-for-profit laboratories, academia, industry, and international space organizations.

Some of the motivation for this new move to revitalize NASA's advanced technology activities can in general be traced to consistent external feedback received from the National Research Council (NRC) over the past several years and, in particular, from the Augustine Committee in 2009. This feedback has urged the Agency to pursue a strategically focused long-range technology development program with an emphasis on 'pushing' specific technology developments rather than relying on the more typical practice of letting mission applications 'pull' certain technologies. The Augustine Committee report (see Reference 1) made the following point on this topic: "*The Committee strongly believes it is time for NASA to reassume its crucial role of developing new technologies for space. Today, the alternatives available for exploration systems are severely limited because of the lack of a strategic investment in technology development in past decades.*"

In the past NASA's science and human exploration missions have strongly relied upon multiple technological advances in GN&C. Some of these GN&C technological advances were achieved with dedicated and sustained investments to mature emerging technologies starting at the low end of the Technology Readiness Level (TRL) scale. With the diminishment of low-TRL GN&C technology investments over the last ten years only minimal evolutionary technological advances have been possible. Most of these were accomplished by leveraging relatively modest amounts of Project funds to package and flight qualify mid-TRL GN&C technologies for specific mission applications.

The current changes within the Agency should have a positive impact on the GN&C discipline given the potential for sizeable investments for GN&C technology development and in-space demonstrations of new

[2] The Defence Advanced Research Projects Agency (DARPA) is the research and development office for the US Department of Defense. DARPA's mission is to maintain technological superiority of the US military and prevent technological surprise from harming our national security. They also create 'technological surprise' for our adversaries. The DARPA technology development model is to constantly innnovate revolutionary 'order of magnitude' high-payoff ideas and then sponsor projects bridging the gap between fundamental discoveries and the provision of new military capabilities.

Autonomous Rendezvous & Docking (AR&D) systems, Autonomous Precision Landing (APL) systems, Entry Descent, and Landing (EDL) systems and possibly Autonomous Systems & Avionics. These technologies are clearly needed to support future missions, especially the envisioned Precursor Robotic Program (PRP) missions that will scout targets for future human activities, identifying potential target destinations, and identifying the hazards and resources. These technologies will also be needed for the future Near Earth Object (NEO), Lunar, and Mars exploration missions that make up NASA's new long-range Human Exploration strategy. The need for these GN&C-related mission-enabling technologies, which will be discussed in Section IV of this paper, has been recognized, and they are currently on the Agency's technology 'drawing board' with plans for their development being formulated. But, what are the other enabling or enhancing GN&C-related technologies needed to support the wide range of NASA's future missions? This paper offers an answer to this question.

II. The GN&C State-of-the-Discipline

All fifteen NASA Technical Fellows periodically perform State-of-the-Discipline (SoD) assessments of their respective engineering disciplines for the NASA Office of the Chief Engineer and for NASA's Chief Safety Officer. In their SoD briefings, Technical Fellows typically outline trends, challenges, and issues facing their individual disciplines and provide a roadmap for improvement. The discipline's readiness to support the goals & objectives of each of the NASA Mission Directorates is evaluated and the technical challenges and barriers currently faced by the discipline are summarized. The SoD assessment also provides advocacy recommendations to respond to observed weakness and challenges. In this section of the paper an executive-level summary of the current NASA GN&C SoD will be presented. The capability of the cross-Center NASA GN&C Community of Practice (CoP) to satisfy the needs of the four NASA Mission Directorates will be specifically addressed following some general background material. This evaluation of the discipline's readiness to support each specific Mission Directorate is not an evaluation of mission plans, content, etc. Rather it is the Technical Fellow's viewpoint supported by interactions and inputs from the NASA Engineering and Safety Center (NESC) GN&C Technical Discipline Team (TDT), the history of NESC Assessment requests and requirements, and participation in multiple Program/Project reviews. This is an evaluation of the readiness of the NASA implementation of the discipline, and is not intended to represent the GN&C engineering and technology capabilities outside NASA.

The GN&C discipline's ability to satisfy the engineering needs and requirements of each Mission Directorate will be evaluated in the following areas:

- Computing and test (or operational) facilities
- Test Flight Opportunities
- Expertise in Tool Application, Tool Development, and Test

The GN&C discipline supports all four of NASA's Mission Directorates. The GN&C discipline covers a very broad range of engineering activities and specialties related to determining, guiding, and controlling the dynamic state of a vehicle as necessary to meet mission objectives. Figure 1 depicts the a typical, simple, generic GN&C system block diagram. The three major separate GN&C functional elements can be defined as follows:

> **Guidance:** the determination of a trajectory from a moving vehicle's current position/velocity/attitude state to a desired position/velocity/attitude state, while satisfying specified constraints such as fuel expenditure, safety, dynamic/thermal loading, and time criticality.
>
> **Navigation:** the determination of the current dynamic state (both attitude and position) of a moving vehicle in a specified frame of reference
>
> **Control:** the determination of the commands to the force and torque actuators on a moving vehicle that both stabilizes and regulates the motion of the vehicle to drive the navigated state towards the desired guidance state, usually in a closed-loop manner

Figure 1 and the above GN&C definitions are helpful as a starting point to explain the GN&C discipline to colleagues in other disciplines, system engineers, project managers, and decision makers; but they do not tell the entire GN&C 'story'. The GN&C discipline is more abstract and less tangible than our sister engineering disciplines. GN&C is much broader and deeper than Figure 1 or what the definitions can convey. The GN&C CoP has a non-technical challenge to communicate to others outside our discipline exactly what the discipline does, how the discipline performs its work, and how it interacts with other disciplines. Most importantly, the GN&C CoP needs to do a much better job of communicating why our discipline should be engaged early, rather than later on mission design and flight system development activities. The GN&C CoP must also work harder at changing the perspective others have of the discipline away from the traditional view of GN&C systems as a single-input/single output (SISO) process with a single controller, towards recognizing that modern GN&C systems can be a distributed heterogeneous collection of physical and information systems, with intricate interconnections and interactions (see Ref. 2).

GN&C engineering consists of a wide range of internally interacting and coupled sub-discipline areas. GN&C is very much a system integration discipline with strong external interactions. Tight engineering process coupling exists with Systems Engineering, Flight Mechanics, Avionics, Software, Mechanisms, Propulsion, Aerosciences, and Loads & Dynamics disciplines. To a lesser degree there is also interaction with the Human Factors discipline and Mission Operations for crewed and robotic flight operations command & control applications. GN&C involvement on a flight project will span the complete system lifecycle from the initial mission formulation phase through flight operations and ending with mission termination.

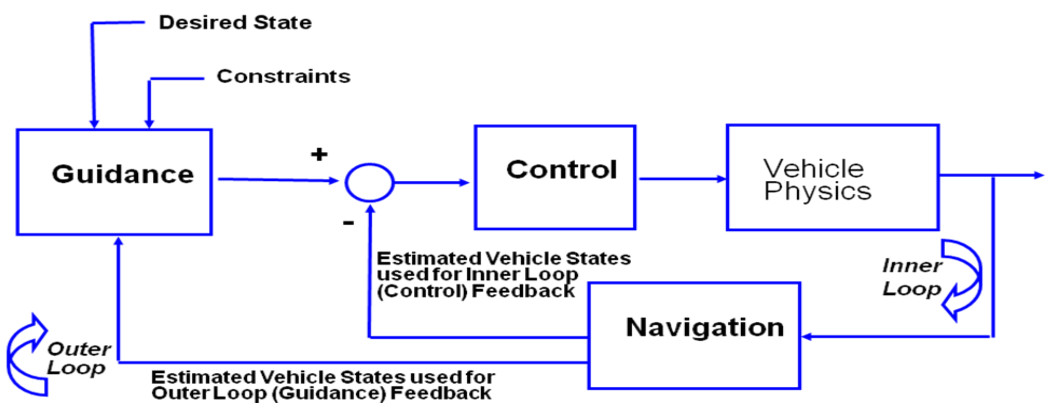

Figure 1. Typical simple generic GN&C system block diagram.

A. <u>Aeronautics Research Mission Directorate</u>

Of the five Programs executed under the sponsorship and management of the Aeronautics Research Mission Directorate (ARMD) there are primarily three which engage the capabilities of the GN&C discipline. These three are: 1) the Fundamental Aeronautics Program, 2) the Airspace Systems Program, and 3) the Aviation Safety Program. Figure 2 is an illustrative photo montage of the research areas and technologies supported directly or indirectly by the GN&C discipline.

The Fundamental Aeronautics Program (FAP) conducts long-term, cutting-edge research in all flight regimes to address the major challenges of modern air transportation: public concern over noise and emissions; the affordability of air travel given concerns about jet fuel supplies and costs; the need for increasing mobility to meet the growth of air transportation; and the need for progress toward faster transportation. FAP also conducts research associated with air-breathing access to space as well as the entry and descent into planetary atmospheres. The FAP has needs for GN&C discipline engineering in the flight vehicle stability and control area for various classes of aeronautical flight platforms. These platform classes consist of hypersonic, supersonic, fixed-wing subsonic, and rotary vehicles. The technical scope of this work ranges from foundational research to multi-disciplinary analysis and optimization.

GN&C related engineering capabilities and technologies are needed to support the Planetary Atmospheric Entry System (PAES) activity which is conducted under the FAP's Hypersonics Project. The ARMD is a co-founder, along with the Exploration Systems Mission Directorate (ESMD) and the Science Mission Directorate (SMD), of a NASA Office of the Chief Engineer (OCE) sponsored multi-year EDL systems-analysis trade study aimed at identifying promising technologies for hypersonic entry and supersonic descent through the Mars atmosphere. The primary objective is to study ways to accomplish dramatic improvements in NASA's current capability to land large payloads safely on planets. This type of up-front technology roadmapping and requirements develop is a critical first step. The results of this EDL systems-analysis trade study, and other such studies, will provide the GN&C CoP with mission-level technology requirements that the can then be pursued by GN&C researchers and engineers in their own discipline-specific areas.

Figure 2.   ARMD Research Areas and Technologies Supported by the GN&C Discipline

Even if we limit our consideration to only the hypersonic capsule and re-entry probe, hypersonic glider, and hypersonic powered glider vehicle classes there are a quite a number of challenging, critically needed GN&C engineering and technology advances that emerge. The hypersonic mission classes will pose unique challenges for the GN&C discipline. Next-generation guidance and control algorithms will need to be developed to address two primary areas here: 1) multi-mission/multi-propulsion element/multiple-Mach flight regimes, and 2) the accompanying ground simulators and flight experiment testbeds.

The capsule and re-entry probes will include application to advanced blunt shapes (manned/unmanned re-supply) as well as planetary probes. Plans for human and large science missions to Mars require nearly two orders of magnitude increase in landed mass. Technologies to enable delivery of higher masses to higher altitudes with greater accuracy need to be developed. NASA cannot continue to rely on the EDL technologies and techniques developed in the 1970's for the Mars Viking lander. The unsolved problem of landing heavy payloads on the surface of Mars should be a focus. The state of the art for successfully landing payloads on Mars is less than 1 metric ton in weight with a landing accuracy of approximately 100 km of the desired target site that is further restricted to lower altitudes. The main challenge is that the Mars atmosphere causes significant thermal heating, but is too thin to enable deceleration to manageable terminal velocities. Factors such as this pose daunting challenges for the system architect, as is the requirement for pinpoint landing (and hazard avoidance) at identified points of scientific interest.

Advanced GN&C techniques are needed to improve landing accuracy, maintaining the vehicle trajectory along prescribed constraints (e.g., minimizing deceleration loads and aeroelastic coupling) as well as to enable precision Mars missions while minimizing expenditure of propellant during final descent. Advanced probe designs (e.g., deployable or ballute designs) permit unique drag-modulation and reduce EDL subsystem mass for accurate placement of payloads/instruments/rovers on the planetary surface.

For hypersonic gliders advanced GN&C technologies are needed to improved trajectory design and landing accuracy given such effects as changing outer mold line (OML) due to Thermal Protection System (TPS) ablation effects and airframe-specific system dynamics such as roll, spiral, Dutch-roll modes. The area of greatest importance, and where the most emphasis should be placed, is in the development of adaptive control which can permit controlled flight across Mach regimes. The adaptive flight control technology is need to address the cases where there is no detailed aerodynamic model available, or there are with excursions away from the model (e.g., unplanned departures from aerodynamic geometry or fault/failure events occur) or for flights that have a very uncertain atmospheric model. Some concepts will drive the need for adaptive flight control during exo-atmospheric skips, or where viscous interaction effects across a large Mach number span is of significance.
Powered hypersonic gliders (e.g., the X-43A) involve the combined effects of the “glider” with a powerplant (e.g., a rocket or a scramjet). These complex systems are typically poorly modeled powered vehicles that have strong system-wide coupling between propulsion and aerodynamics, and have thin performance margins necessitating operation near system constraints to achieve efficiency. In general, this level of integrated system-level multi-disciplinary functionality in and of itself will represent a major technology advance with the GN&C discipline playing a significant role. The current generation of linear flight control systems will not be adequate to handle the complex control, plant, fluid flow, structural and thermal dynamic interactions and non-linear coupling effects. In these applications an adaptive hierarchical flight control structure interacting with simpler sub-system controllers might be a particularly attractive solution to the problem (see Ref. 3).

GN&C-derived concepts, capabilities, and technologies for high-capacity, efficient, and safe operations in the National Airspace System (NAS) for 2025 directly support ARMD’s Airspace Systems Program (ASP). The primary goal of the ASP is to develop revolutionary concepts, capabilities, and technologies that will enable significant increases in the capacity, efficiency and flexibility of our NAS. In pursuit of this goal, the ASP has aligned its research portfolio to directly address the Air Traffic Management (ATM) research needs of the Next Generation Air Transportation System (NextGen) Initiative as defined by the multi-federal agency Joint Planning and Development Office (JPDO). The GN&C discipline supports one of the two major NextGen ATM projects: the NextGen-Airspace Project. This effort focuses on developing capabilities in traffic flow management, dynamic airspace configuration, separation assurance, and airspace super density operations, which are supported by cross cutting technical areas of trajectory synthesis, prediction, uncertainty, performance based services, and system-level design, analysis and simulation tools. The GN&C discipline supports, in a non-traditional role, the research being performed to address Four-Dimensional Trajectory Operations, including advances in the science and applications of multi-aircraft trajectory optimization that solves the demand/capacity imbalance problem while taking into account weather information, forecast uncertainties, and keeping aircraft safely separated. The project's research seeks to develop and test concepts for advanced traffic flow management to provide trajectory planning and execution across the spectrum of time horizons from "strategic planning" to "separation assurance." The project will also conduct research to explore dynamic airspace configuration that addresses the technical challenges of migrating from the current structured, static homogenous airspace to a dynamic, heterogeneous airspace that adapts to user demand and meets changing constraints of weather, traffic congestion, and a highly diverse aircraft fleet. The roles and responsibilities of humans and automation are also addressed under this project.

The GN&C discipline also supports ARMD’s Aviation Safety Program which explores all of the issues associated with making an already safe air transportation system even safer. Research focuses on ways to further reduce risk in a complex, dynamic operating domain. The Aviation Safety Program works with its partners to address the challenges created as the nation transitions to the Next Generation Air Transportation System. These challenges include significant increases in air traffic, continued operation of legacy vehicles, introduction of new vehicle concepts, increased reliance on automation, and increased operating complexity. The program seeks to provide more ways to predict and prevent safety issues, to monitor for safety issues in-flight and lessen their impact should they occur, to analyze and design them out of complex system behaviors, and to constantly analyze designs and operational data for potential hazards. Of the four research areas within Aviation Safety the GN&C discipline is most heavily engaged in investigating and understanding methods to lessen the effects of aircraft upset and uncommanded loss of control (Integrated Resilient Aircraft Control Project) as well as developing improved ways to predict and manage the overall health of an aircraft in flight (Integrated Vehicle Health Management Project). To a lesser degree the GN&C discipline supports a third project whose objective is to provide design methods and analysis tools for properly integrating human contributions to safety in the future flight deck arena (Integrated Intelligent Flight Deck Project).

Some of the most challenging GNC technologies needed to support ARMD's goals and objectives include GN&C systems for Unmanned Air Vehicles (UAVs) with various levels of autonomy; Intelligent Flight Control (IFC) using non-classical multivariable adaptive control; hypersonic flight control systems; the dynamic allocation of airspace structure; and controller resources using advanced air traffic trajectory prediction capabilities to support adaptive traffic flow management.

In summary, the ability to satisfy ARMD's GN&C engineering needs and requirements was evaluated as follows:

- Computing facilities
- Test facilities
- Test Flight Opportunities
- Expertise:
  - Tool Application
  - Tool Development
  - Test

The 'traffic light' color code used for this ARMD evaluation , as well as for the other three Mission Directorates, is defined as follows:

Green - Discipline adequately positioned to meet mission requirements, No serious risks or issues to execution of Mission. No near-term action required.

Yellow – Discipline has marginal ability to meet Mission requirements, Some risk to execution of Mission. Near-term corrective actions required.

Red – Discipline is inadequately positioned to meet mission requirements, Serious risk and/or issues to execution of Mission. Immediate action required.

The above ARMD evaluation does not take into account any of the recent changes occurring within NASA as a result of the President's Budget Request release in February 2010. The above evaluation was initially performed in September 2007 and updated again as of late 2009.

B. <u>Exploration Systems Mission Directorate</u>

As the Space Shuttle approaches retirement, NASA's Exploration Systems Mission Directorate (ESMD) has been leading multiple programs and projects to build the next fleet of vehicles to service the ISS and return humans to the moon, and possibly to Mars and beyond. In support of these efforts, the ESMD is performing field tests, designing surface systems and conducting advanced human research to ensure that future missions are safe, sustainable and affordable. The GN&C discipline has been supporting the efforts of the Constellation Program (CxP) to develop an Orion CEV, a Launch Abort System (LAS) for Orion, and the Ares-I crew launch vehicle. Figure 3 is an illustrative photo montage of the ESMD missions and technologies supported directly or indirectly by the GN&C discipline.

NASA's GN&C engineers have also been supporting the ESMD's Advanced Capabilities Division (ACD), which is composed of three major programs: the Lunar Precursor Robotic Program (LPRP), Human Research Program (HRP), and the Exploration Technology Development Program (ETDP). These ACD programs and their projects provide knowledge as a result of ground-based research and technology development, research conducted in space, and observations from robotic flight missions. ACD also develops and matures advanced technology, integrates that technology into prototype systems, and transitions knowledge and technology to the CxP. Through its activities ACD provides operational and technical risk mitigation for NASA future exploration endeavors.

Figure 3. ESMD missions and technologies supported by the GN&C discipline

As mentioned in the Introduction of this paper NASA is currently in the process of shifting to a new approach for Human Exploration. Thus, currently there is significant uncertainty in the future of the CxP as it is being restructured. Several new programs have been formed seeking to create a new affordable and sustainable human space exploration enterprise. NASA has formed multiple study teams to investigate various implementation options for taking the Agency in these new directions, if and when authorized by Congress. In particular there is a high level of interest in developing the 'Flexible Path' strategy to extend human presence beyond LEO. The extension of ISS operations to at least 2020 opens the door for using that 'national laboratory' as a testbed for maturing and demonstrating new exploration technologies, GN&C-related technologies in particular. Also NASA's Commercial Crew and Cargo Program is investing financial and technical resources to stimulate efforts within the private sector to develop and demonstrate safe, reliable, and cost-effective space transportation capabilities. These significant changes are occurring at the same time that plans are being formulated to retire the Space Shuttle in 2011. As mentioned above, although the Agency's philosophy and approach to exploration will apparently change, NASA's fundamental human spaceflight goal remains the same: to send human explorers into the solar system to stay.

Regardless of all the changes occurring within NASA and within the ESMD it is quite likely that robust & reliable GN&C systems for ascent, abort, on-orbit and re-entry mission phases, which support crew safety and mission success goals, will still be required. The GN&C CoP will be called upon to support the Commercial Crew and Cargo Program to ensure safe and reliable crew transportation to the ISS.

ESMD challenge areas for the GN&C discipline include:

- Autonomous Rendezvous, Proximity Operations & Docking/Undocking
- Launch Abort System (LAS) stability & control
- Robust Adaptive Control of Flexible Launch Vehicles
- Establishment of spacecraft flying qualities
- End-to-End testing of GN&C systems for human exploration
- Autonomous Precision Landing and Hazard Avoidance
- Probabilistic control methods for complex, real-world GN&C engineering problems such as EDL .
- Integrating GN&C technologies for system-level Integrated Vehicle Health Management (IVHM) functions

One particular GN&C engineering challenge currently confronting ESMD is the stabilization and flight control of the Orion Launch Abort Vehicle (LAV). This is an issue that has been extensively studied not only by the responsible NASA and contractor project-level engineers but also the NESC GN&C and Aerosciences and Flight Mechanics TDTs. The LAV has had difficulty meeting its performance requirements in the transonic flight regime in the 0.9 to 1.3 Mach number regime. The LAV GN&C teams, and others working the problem, have been considering the possibility that the system they are dealing with cannot be adequately characterized using the tools and resources available to them. There actually may not be solutions to the problems they are facing and in fact, they may be trying to qualify a design concept that is physically and mechanically incapable of meeting the performance requirements. To further emphasize the severity of this issue, it should be noted that the transonic flight regime is a notoriously stressful mission phase. Many atmospheric flight vehicles have suffered performance degradation, damage, and failure during their passage through the transonic flight regime. If there is a point in the Ares-I ascent trajectory where the Orion crew will depend on robust and reliable LAS operation, it may be as the launch vehicle passes through transonic regime near the maximum dynamic pressure (MaxQ) condition.

At the heart of this problem is the LAV Abort Motor Jet Interaction (AMJI) issue. Recent aerodynamic analyses using Computation Fluid Dynamics (CFD) have shown a severe loss in LAV's Attitude Control Motor (ACM) pitch control authority due to an asymmetry in the ACM plume path as it interacts with the Abort Motor (AM) plume. This CFD analysis predicts as much as 80% loss in pitch effectiveness is experienced, again in the transonic flight regime, due to this asymmetry. In addition a high yawing moment is induced on the vehicle as the ACM plume is diverted to one side or the other of the AM plumes. Much technical effort has recently gone into characterizing the nominal aerodynamic performance of the LAV with the AM firing and the associated uncertainties in these predictions. At present the LAV is capable of meeting performance requirements when flying under the assumption of nominally predicted vehicle aerodynamics, but uncertainties cause the vehicle to tumble for a significant number of cases in the transonic flight regime. The focus has been on the aerodynamic uncertainties since they presumably are the culprit in causing the vehicle to miss performance expectations, but there continues to be significant concern surrounding the construction and validity of the AMJI nominal database. The issue is further complicated by the lack of wind tunnel test data that accurately simulates the AMJI problem. The simulations to date that show the LAV tumbling in the transonic flight regime all assumed a fully capable (and uncoupled) ACM pitch (and yaw) authority. These results have driven the need to investigate alternative means of improving stability and flight control performance of the LAV (e.g. by the addition of inert ballast mass). In parallel, special wind tunnel tests are being pursued in an effort to first determine if the CFD analyses are realistic, and if so, lower the uncertainties in the aerodynamic database.

The GN&C and Aerosciences teams working to resolve this particularly challenging flight system problem are considering their LAV re-design options. Some of these options were reviewed by the NESC as part of the Constellation System Preliminary Design Review (PDR) and feedback was provided to CxP program management in the form of an NESC White Paper report (see Ref 4). Beyond the 'simple' ballasting option there was a second approach being considered that would be to employ a stability augmentation system similar to that used on the Russian Soyuz launch abort vehicle. This system uses deployable grid or lattice fins that are stored close to the vehicle's Outer Mold Line (OML) for nominal flight and which are extended during an abort scenario. The grid fins operate in a static mode when they are deployed and add aerodynamic area aft on the vehicle to enhance pitch and yaw stability. If needed, the individual fins could also be mounted on a rotary actuator and pitched to provide active control during LAV operation. This type active control capability has been implemented on several missile designs.

A third and even more elegant approach would be to add permanently deployed, actively controlled, conventional fins to the LAV. The fins would be sized for launch abort vehicle operations and employed active pitch control during an abort. During nominal operations, the fins were assumed to be fixed. The fins were found to be quite effective in controlling the LAV during an abort, particularly when coupled with the existing ACM. However, the fins also provided normal force and pitching moments on the nominal vehicle during ascent that increased the bending moments on the Ares-I launch vehicle. To counter this effect the fins could be actively pitched throughout the nominal ascent of the launch vehicle. In this mode of operation, the fin control laws could be tailored to actively reduce stack bending moments, improve crew ride quality, and/or damp solid rocket motor thrust oscillations at the crew's location. However, this approach would make the Ares-I launch vehicle reliant on an Orion system to fly its nominal mission. Thus the Orion spacecraft would no longer be a payload for Ares, but part of an integrated flight control system.

Clearly the LAV problem described above points to the need to improve GN&C analysis, as well as modeling and simulation, capabilities for this class of aeronautical vehicle. Investments also need to made to improve NASA's facility capabilities to adequately test launch abort system design concepts. This should be done in a multi-disciplinary technical partnership with the sister disciplines of Aerosciences and Flight Mechanics. Consider that, were NASA in a position to implement it, an adaptive flight control system for the LAV might have been the superior solution to ensuring the abort vehicle's stability and robust and reliable flight control in the transonic flight regime. An abort system will likely be an integral part of any future NASA-developed or commercially-developed human rated launch vehicle system so this type of problem will not be going away with the restructuring of the CxP. The creation of a feasible and implementable adaptive flight control capability should be a high priority objective of future GN&C technology development programs.

In summary, the ability to satisfy ESMD's GN&C engineering needs and requirements was evaluated as follows:

- Computing facilities
- Test facilities
- Test Flight Opportunities
- Expertise:
  - Tool Application
  - Tool Development
  - Test

C. Science Mission Directorate

NASA's Science Mission Directorate (SMD) conducts scientific exploration that is enabled by access to space. SMD projects humankind's vantage point into space with observatories in Earth orbit and deep space, spacecraft visiting the Moon and other planetary bodies, and robotic landers, rovers, and sample return missions. From space, in space, and about space, NASA's science vision encompasses questions as practical as hurricane formation, as enticing as the prospect of lunar resources, and as profound as the origin of the Universe. The capabilities of the GN&C discipline are called upon to support missions in all the major Divisions of the Science Mission Directorate (SMD): Earth Science, Heliophysics, Planetary Sciences, and Astrophysics. Figure 4 is an illustrative photo montage of the missions supported directly or indirectly by the GN&C discipline.

GN&C services, systems and technologies are provided to enable and enhance Space & Earth Science robotic missions in various operational environments: LEO, Geosynchronous (GEO), High Earth Orbit (HEO), Lunar and Cis-Lunar, Planetary, Deep Space, and Lagrange point regimes. GN&C engineers within NASA provide hands-on design, development and test functions, subsystem management services as well as experienced insight/oversight support on the total spectrum of SMD robotic mission classes, each of which has different prescribed levels of performance, fault tolerance, reliability, risk, and affordability.

The specific challenges faced by the GN&C CoP in satisfying SMD's GN&C engineering need and requirements include the following:

- Observatory-class precision telescope line-of-sight stabilization, pointing, and tracking
- Planetary aerobraking, aerocapture and Entry, Descent, & Landing (EDL)
- Pinpoint landing and hazard avoidance for planetary exploration
- Autonomous rendezvous and docking for planetary sample return
- Architectures, systems, components for multi-spacecraft Precision Formation Flying
- Low power/mass/volume and reliable GN&C sensors and actuators for planetary and Smallsat missions
- Higher resolution/lower jitter Earth observation platforms, sensors and instruments

Figure 4. SMD Missions Supported by the GN&C Discipline

Consider just the first of those SMD GN&C challenges listed above. The GN&C engineers at NASA can anticipate increasingly challenging requirements for telescope pointing control and jitter suppression to be placed on them in the future. Just in this one area significant GN&C technology development investments will be required, such as:

- Pointing Sensing and Control (e.g., Fine Guidance Sensors (FGS's), inertial sensors, fine resolution/high bandwidth actuators, etc)
- Image Stabilization (e.g., Inertial Pseudo Star Reference Unit (IPSRU) "like" technologies, image post-processing algorithms and dedicated image stabilization processors, etc.)
- Wavefront Sensing and Control (e.g., advanced optics, wavefront sensors, fast steering mirrors, high bandwidth actuation, optical path length control (delay line) devices, etc.)
- Optical beam stabilization, Pointing, Acquisition & Tracking (PAT) for high data rate optical (laser) communications of science data to the Earth
- Active Vibration/Jitter Sensing and Control
- End-to End Integrated Dynamic Modeling techniques and methods to study the interactions between the GN&C, optic, structures, thermal, power, etc. subsystems
- Multidisciplinary design, analysis and optimization tools to integrate diverse discipline inputs to initially size an observatory configuration and to predict overall system performance. These tools will support the observance of multiple individual discipline constraints in a system level architecture and judiciously balance the allocation of requirements to subsystems.

Technology investments for the development of reliable optical communications systems (e.g., Laser communications or 'Lasercom') would fundamentally alter NASA's science mission strategies by providing revolutionary data collection capabilities. Optical communications technology has the potential to relay extremely high data rates using space terminals of very low size, mass, and power. Lasercom systems would allow data downlink rates on the order of 1 Gbps from the Moon, 0.1 Gbps from Venus /Mars or 1-10 Mbps from the outer planets. Lasercom systems would also enable unprecedented ranging capabilities (e.g., cm-level positional accuracy or potentially mm-level) thereby providing orders of magnitude improvement in positional accuracy for geodynamic studies involving gravity and topography. Lasercom capabilities would allow for Earth-style planetary remote sensing campaigns at planets such as Venus and Mars, Jupiter and its moons.

It is quite likely that future large space telescopes will have a very different configuration than those that are currently in orbit and therefore will face unusual attitude control and momentum management challenges. As a case in point consider Figure 5 which depicts the Hubble Space Telescope (HST) LEO on-orbit configuration versus that of the James Webb Space Telescope in its second Sun-Earth Lagrange Point (L2) orbit. The HST operates in a low Earth orbit and uses a large stiff tube to shield its optics from the Earth's albedo. The entire HST spacecraft is controlled to point its primary mirror at science targets for tens of minutes at a time before Earthshine intrudes into the telescope keep-out-zone. The James Webb Space Telescope (JWST), scheduled for launch in 2014, will fly in an orbit around the L2 orbit about 1.5 million kilometers (km) from Earth to avoid the problems associated with LEO operations. Continuous pointing at a target for many hours will be possible. Telescopes at L2 will typically have open optics on the anti-Sun side of a large Sunshield. The Sunshield on JWST is 22 m x 12 m, approximately the size of a tennis court.

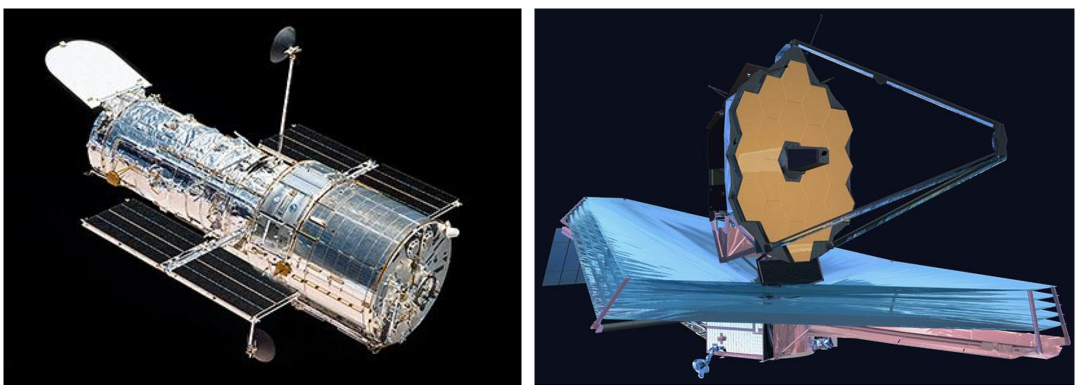

Figure 5. The Hubble Space Telescope LEO on-orbit configuration (left) versus that of the James Webb Space Telescope in its L2 orbit (right)

JWST's large primary mirror consists of eighteen (18) deployable segments each about the size of the single HST mirror. The segments must be controlled relative to each other to achieve an effective telescope aperture of 6.5 m. Several technical challenges in the areas of wavefront sensing, actuation, modeling, and controls arise in the design and implementation of such a control system. The JWST spacecraft bus and the flexible sunshield are attached to the telescope optics and they all move together to new science targets. The large flexible JWST observatory cannot be pointed as accurately as the smaller rigid HST. However the same science pointing accuracy of $7/1000^{th}$ of an arcsecond will be achieved using a fine steering mirror after the secondary mirror in the telescope optics. Control of all of the optics associated with the JWST mission requires development of technologies for precision pointing and vibration attenuation.

Momentum management on HST is achieved by commanding magnetic torques to desaturate the angular momentum that accumulates in the reaction wheels. Magnetic torquing is not possible at L2, so JWST must use thrusters for wheel desaturation. The large Sunshield severely restricts the directions in which thrusters can fire. Consequently JWST must be reoriented periodically so that the thrusters can produce the desired inertial desaturation torques. JWST has added a large trim tab at one end to help balance the solar radiation pressure torques largely due to the asymmetric shape of the Sunshield. The trim tab deployment angle on JWST is fixed before launch based on torque predictions for the latest values of system CM location, Sunshield dimensions, and surface properties. Never the less GN&C challenges arise given the considerable uncertainty in the predictions of the rate of momentum accumulation due to modeling uncertainties and the infinite possible time histories of observatory attitude in the actual mission. Subsequent Sunshield designs will probably have controllable trim tabs to better balance environmental torques and thereby extend mission life.

Another indirect challenge that the JWST mission presents to GN&C engineers is concerns the development of methods and techniques for servicing the JWST in its L2 mission orbit. Advances in rendezvous technologies and capabilities in tandem with advanced servicing tools and methods will be needed in order to contemplate the servicing of robotic science spacecraft in non-LEO orbits such as L2.

In summary, the ability to satisfy SMD's GN&C engineering needs and requirements was evaluated as follows:

- Computing facilities
- Test facilities
- Test Flight Opportunities
- Expertise:
  - Tool Application
  - Tool Development
  - Test

As is the case for the other Mission Directorate evaluations, the above SMD evaluation does not take into account any of the recent changes occurring within NASA. The above evaluation was initially performed in September 2007 and updated again as of late 2009.

D. Space Operations Mission Directorate

The Space Operations Mission Directorate (SOMD) provides the Agency with leadership and management of NASA space operations related to human exploration in and beyond low-Earth orbit. The current exploration activities in LEO that fall under the SOMD's purview are the Space Shuttle Program (SSP) and the ISS Program. The directorate is similarly responsible for Agency leadership and management of NASA space operations related to Launch Services, Space Transportation, and Space Communications and Navigation (SCaN) in support of both human and robotic exploration programs. Figure 6 is an illustrative photo montage of the SOMD operational missions and technologies supported directly or indirectly by the GN&C discipline.

First and foremost the GN&C discipline provides sustaining engineering services for safe and reliable SSP and ISS flight operations. Maintaining the safety of the Shuttle crews and the ISS crews is of paramount importance. NASA's GN&C engineers also support the development of advanced concepts, designs, and technologies for advanced mission support systems for tracking, navigation & communications.

Some of the SOMD's GN&C-related challenges are:

- High capacity communications systems
- Integrated navigation & communications systems support ESMD & SMD missions
- On-board navigation alternatives to traditional ground based tracking and orbit/trajectory determination
- Optical beam stabilization, Pointing, Acquisition & Tracking (PAT) for high data rate optical (laser) communications

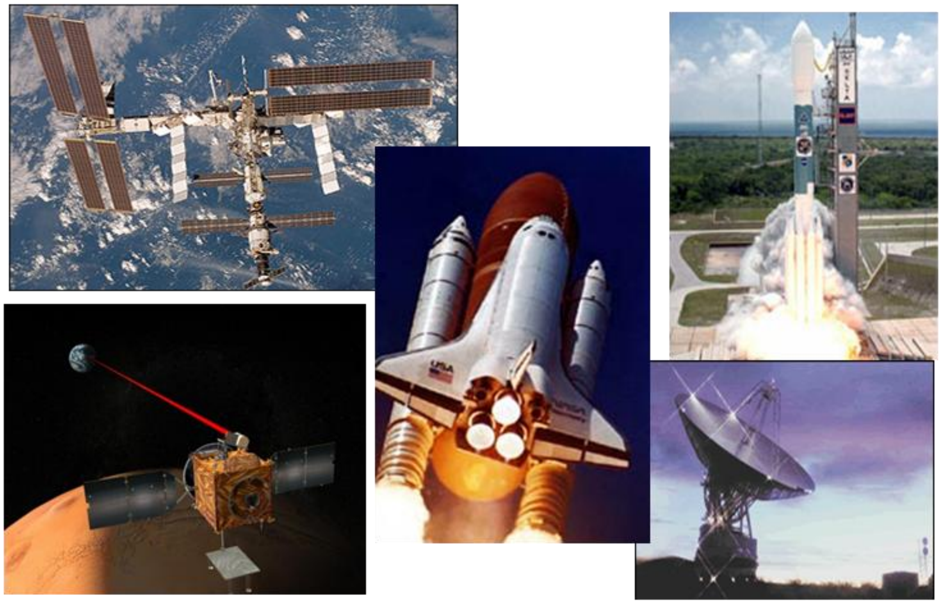

Figure 6. SOMD missions and technologies supported by the GN&C discipline

Lasercom is one important area in which the GN&C discipline is supporting the SOMD's technology development initiatives. The Lunar Laser Communication Demonstration (LLCD) Program, sponsored by the SOMD, will be the first NASA space Lasercom system to be flown. The LLCD inertially-stabilized space terminal, being designed and built by the Massachusetts Institute of Technology's Lincoln Laboratory, will fly on Lunar Atmosphere and Dust Environment Explorer (LADEE) spacecraft which is scheduled to be launched in 2013 from Wallops Island on a Minotaur V expendable launch vehicle. GN&C engineers from NASA are supporting the development of the Lasercom uplink and downlink stabilization, pointing, acquisition, and tracking systems.

Another area where GN&C engineers support the SOMD is in their SCaN developments. The SOMD's SCaN supports LEO, MEO, HEO, GEO, lunar, libration, deep space missions across all phases of their life cycle (e.g., formulation, design, development, test, operations, & disposal). There is an over-reliance on technology investments made decades ago. Some navigation capabilities have eroded in many areas resulting in cause for concern and these should address as part of NASA's renewed emphasis on technology development. Certain tracking and navigation facilities are aging they require modernization. The internal Information Technology (IT) architectures also require upgrades for lower sustaining costs and greater operational flexibility. These specific upgrades should include enhanced internal data processing, data interfaces and process controls. Legacy orbit determination (OD) systems require replacement as well given their age, high maintenance costs, and limited flexibility. For example, the Goddard Trajectory Determination System (GTDS) is ~40 years old. Some of these legacy OD systems are stressed or unable to support the more complex, highly dynamic missions NASA is currently developing such as JWST and the Magnetosphere Multiscale Mission (MMS). Challenges with navigation tools include the need to satisfy new requirements for trajectory optimization, the handling of continuous low-thrusting spacecraft, the advent of new navigation measurement types, and to support advanced mission design architectures/design concepts. Beyond these critical navigation needs there is a near-term need for NASA to invest in the following areas:

- The development of tools to perform integrated end-to-end simulations to assess full navigation system interfaces and performance
- Advanced navigational system research, to develop the new concepts, algorithms, approaches, and systems needed to meet the needs of the more complex and highly dynamic missions. This research should be focused in the following areas:

- Tracking and Data Relay Satellite System (TDRSS) navigation enhancements
- On-board navigation
- Relative navigation
- Visualization tools
- Lunar surface navigation
- Celestial navigation
- Optical Navigation
- Navigation data simulation tools
- Autonomous pose estimation algorithms and systems
- Beacon navigation algorithms and system concepts

In summary, the ability to satisfy SOMD's GN&C engineering needs and requirements was evaluated as follows:

- ➢ Computing facilities
- ➢ Test/Operational facilities
- ➢ Test Flight Opportunities
- ➢ Expertise:
  - – Tool Application
  - – Tool Development
  - – Test

III. GN&C Challenges and Critical Needs

Three key GN&C challenge areas will be discussed in this section of the paper. The first challenge has to do with the fact that advanced GN&C capabilities are not being exploited as much as they could be due to perceived risk of implementation. The second challenge concerns the lack of meaningful investments in the next generation of GN&C component-level technologies. The third challenge arises from the lack of consistent Agency-wide top-level guidelines for GN&C system Design, Development, Test & Evaluation (DDT&E). In the remainder of this section each of these three challenges will be discussed and some recommendations to mitigate those challenges will be put forward.

A. <u>Greater Exploitation of Modern GN&C System Capabilities</u>

Significant advances in NASA mission capabilities are being constrained by a lack of awareness, investment, and infusion in advanced GN&C capabilities due to perceived risk of implementation. There is a substantial body of Research and Development (R&D) work in "modern" optimal state-space methods already in place for multivariable adaptive GN&C systems. Such systems offer the potential of greatly improved performance, operational flexibility, 'on the fly' adaptive reconfiguration, and/or new system capabilities but are rarely exploited in NASA's operational flight systems. NASA's GN&C workforce demographics supports greater consideration of these modern methods since the youngest generation of GN&C engineers has been educated in use of optimal state-space methods for multivariable adaptive control. It would be advantageous to investigate, better understand, and specifically define the barriers that are inhibiting and constraining their application/infusion into NASA missions. The Verification & Validation (V&V) process for multivariable adaptive systems is one such barrier that is already well recognized but it is not fully quantified or understood.

To address this challenge NASA should develop an improved characterization of the risk/benefit of implementing modern GN&C systems. In particular the Agency should identify those driving mission applications for multivariable adaptive GN&C systems where the risk/benefit trade is most favorable. This work would involve the investigation of possible approaches and layout roadmap for flight testing needed for safe and reliable application of multivariable adaptive GN&C systems for NASA mission applications. There is an opportunity here to leverage Department of Defense (DoD) investments to develop V&V strategies and technical approaches for multivariable adaptive flight control systems.

B. <u>Greater Investment in GN&C Component Technologies</u>

The period of years, if not decades, in which there has been a lack of meaningful NASA investment in next generation of GN&C component-level technologies has had the consequence of constraining GN&C system architects and designers. This particular area was identified as top GN&C technical challenge in 2009 GN&C CoP survey (see Reference 5). There has been little or no funding for GN&C technology "seedling" projects to investigate feasibility of new low-TRL sensor or actuator concepts. This situation is exacerbated by weaknesses in the GN&C component (Sensor/Actuator/ Processor) industry/vendor supply chain after years of industry consolidation that limit GN&C system architecture/design concepts. There is minimal funding for technology development testbeds to mature mid-TRL GN&C component technologies. NASA is missing an opportunity to leverage significant DARPA investments in Micro ElectroMechanical Systems (MEMS) inertial sensors for certain spacecraft GN&C applications.

Some relevant observations on the state of the aerospace industrial base are appropriate here. The health of the subtier 'niche' component suppliers has a direct influence on NASA's ability, and that of the large aerospace prime contractors, to actually build the GN&C systems needed for the our robotic and crewed spacecraft vehicles. In this context we are talking about GN&C subsystem components such as star trackers, star cameras, inertial sensors (gyroscopes and accelerometers), sun sensors, reaction wheels, momentum wheels, gimbals and other pointing actuators, reaction control thrusters, pyrovalves, etc. One level down the ability of the US industry to produce GN&C components is constrained by underlying issues with electronic piece parts (e.g., diodes), read-out integrated circuits (ROICs), mechanical bearings, detector focal plane arrays, cryocoolers, clocks, and , in some cases, raw material sourcing limitations. The DoD has the same concerns as NASA in this area.

Over the past several years there has been an apparent obsolescence of some US domestic GN&C space-qualified component production capabilities as the same time that several foreign countries have developed significant indigenous component production capabilities. This obsolescence is most often attributed to the following causes:

- Industry consolidation (mergers and acquisitions)
- Retirement of highly-skilled industrial workforce
- Lack of domestic critical engineering skills to replace aging industrial workforce
- Insufficient research investment
- Disinvestment in critical production and test assets
- Low profit margins on low volume space-qualified unit production rates (relative to commercial units)
- Loss of market share due to uneven competitive playing field vs. foreign component suppliers
- Cost and schedule risks placed on the subtier suppliers (not the primes) to qualify new components
- Dynamic challenges of the space marketplace (funding instabilities)
- Tightened export controls (which indirectly encourages foreign competition)
- Cost and infrastructure burden of the environmental/safety regulations imposed on the relatively small (as compared to the primes) subtier suppliers

There are fewer US domestic component vendors in the marketplace after significant industry consolidation. It appears that some of these remaining US GN&C component vendors are, at best, maintaining only their legacy component product lines. In the absence of any significant NASA investment these component suppliers are reluctant to invest their own limited Internal Research and Development (IR&D) resources to advance the space-qualified component technology.

The overall result is that, for various reasons, foreign component vendors are now supplying several US GN&C system developers. Now 'export control free' space-qualified components, such as star trackers and inertial sensors, are being procured from overseas suppliers at a significant cost reduction as compared to the cost for the equivalent domestically-produced device. Foreign component technology is now on par with, or in some cases, apparently superior to domestic component technology. For example, the state-of-the-art space gravimetric instruments are produced in Europe.

This increased reliance on foreign component suppliers has raised the risk of assured access to critical technology at the DoD. NASA should have similar concerns as the domestic component supply chain shrinks and this starts to place significant constraints on our GN&C design options. The DoD level of concern on this issue is such that a Critical Technologies Working Group (CTWG) has been formed to established a process for strategic management of critical space systems and capabilities. The US Air Force's Space and Missile Systems Center (SMC) has formulated a SMC Critical Technologies list. Items such as atomic clocks, star trackers, reaction wheels, infrared detectors, ROICs, cryocoolers, diodes, and visible sensors appear on a partial list of SMC Critical Technologies (See Ref. 6).

Besides the issue concerning the lack of domestically produced advanced-technology components available for infusion in NASA space systems there is another problem within the industrial base rearing its head. Several of the subtier component manufacturers appear to have lost the 'recipes' for building their high quality spacecraft components. There have been design, test and mission assurance breakdowns causing increased project risks, schedule delays and cost increases. The DoD, as well as NASA, has been hit hard by hardware and software problems at the component and subsystems level. Most experts blame this on a "lack of attention to detail" during production and test. The root cause is tied closely to the recent retirement of highly-skilled industrial workforce members and the lack of critical engineering skills to replace aging industrial workforce.

Dr. Gary Payton, the Deputy Undersecretary of the Air Force for Space Programs, recently commented on this unfortunate syndrome during a February 4th 2010 media event sponsored by the Space Foundation (see Ref. 7) . "*We have been finding during assembly, integration and test problems on satellites and on launch vehicles,"* Payton said. *"Valves on launch vehicles, gyroscopes and reaction wheels on satellites, [these are where] we've been finding problems. Also we've been finding test execution problems in the clean room."* The problems stem from a young and inexperienced work force that is replacing experienced engineers and scientists from the baby-boom generation, Payton said, according to Reference 7. It is not necessarily that this current generation of aerospace workforce is less talented than the prior generation but rather that there are fewer skilled engineers and technicians entering into the field. This workforce situation is then exacerbated in some cases by a lack of emphasis on process control and the dissemination of the lessons learned by the previous generation during the component fabrication and test process. Seemingly small process escapes have resulted in major consequences. However, Payton also said, the component quality issues are also related to the methods by which the government builds and tests its systems, which during the 1990s and early 2000s strayed from the fundamentals that were a staple of previous decades. To combat this problem the US Missile Defense Agency (MDA) has recently created a quality control organization that now has about 130 employees embedded at many of its contractors' facilities. The MDA, as part of an overall approach to resolve their hardware and software quality issues conduct two-week, in-plant reviews of those contractors that MDA feels are having difficulty. If the current trend continues NASA may have to adopt many of the same intensive measures to ensure the quality of our GN&C components.

In some case there is now only one or two domestic sources for certain space systems components. Although this is not a GN&C issue it is worth noting that there is now only one US supplier of Travelling Wave Tube Amplifiers (TWTAs) used in spacecraft communication systems. This condition has raised government concerns about a possible TWTA supply disruption if the sole remaining domestic vendor drops out of the marketplace. This should be a warning sign for the Agency in general and for the GN&C CoP in particular since we are now close to having that same single/sole source situation for certain sensors and actuators. Besides the obvious effect of seriously constraining GN&C system designs there are two other potential risks for NASA of having only a single vendor for a given type of component: the risk of monopolistic pricing and the risk of a "no bid" decision by the sole remaining vendor.

To avoid all these undesirable situations NASA, perhaps in collaboration with the DoD, should be doing more now to preserve, rejuvenate, and enhance the remaining domestic space system component supply chain. This could be accomplished with a balanced combination of targeted component-level technology investments, export control policy changes to enhance domestic competitiveness, performance/interface standardization, large-scale common buys by multiple government programs, mandated government program 'buys'. NASA may also have to more seriously consider the option of more routinely designing and building certain GN&C niche components if the aerospace industrial base can no longer deliver those devices, with assured levels of quality, on schedule and within cost. There may even be a small short-term market, for some commercial companies to go into the business of fabricating, in an “build to print” manner, legacy GN&C components discontinued by the subtier providers but still needed by NASA until new technologies make them completely obsolete

Should NASA have new component technologies to demonstrate it would be a challenge to get them into the space environment for testing. There are at best few flight test opportunities for the demonstration of low or mid-TRL GN&C components in the space environment. Recent history shows the lack of flight test opportunities is also impacting maturation of GN&C system-level capabilities. The New Millennium Program (NMP) Space Technology 9 (ST-9) Pinpoint Landing system technology demonstration mission was initially selected for an “extended Phase A”, then was challenged to cut their costs by 40% , and subsequently, in 2007, was not selected for Phase B. It is hoped that the advent of the new Flagship Technology Demonstration (FTD) Program and the Enabling Technology Development and Demonstration (ETDD) Program will address the egregious lack of test flight opportunities.

Until that time, to address this challenge, the Agency should develop prioritized a cross-NASA needs list, and associated top-level plans and developmental roadmaps, for GN&C component/system technologies. A reasonable and low-cost first step in this process is to review previous work performed at HQ and at the Centers on GN&C technology development and flight demonstration plans/roadmaps. The identification of GN&C technologies, at all TRL levels, now in development should also be performed to allow the CoP and decision makers to see the current ‘big picture’.

Once these preliminary action have been performed NASA should search for and identify the following:

- Areas of overlapping or common GN&C technology needs across NASA’s Mission Directorates
- Multi-disciplinary technology needs/drivers with other disciplines such as avionics, software, flight mechanics, aerosciences, robotics, modeling & simulation, etc.
- Opportunities to leverage R&D investments by other government organizations, national labs and industry, and international partners
- Projects that are suitable for a rapidly initiated demonstration of integrated system-level GN&C technology capabilities
- Initial pathfinder efforts to be led by NESC GN&C TDT with supporting engagement/participation of broader GN&C Community of Practice

C. Develop Guidelines Handbook for GN&C System Design, Development, Test & Evaluation (DDT&E)

There is a lack of consistent Agency-wide top-level guidelines for GN&C system DDT&E. Having such guidelines is viewed as a critical common need by NESC’s GN&C TDT. A review of historical records reveals several GN&C-related mishaps and anomalies caused by breakdowns/lapses in the GN&C systems engineering process. Individual flight projects currently devote considerable time and effort to establishing, interpreting, negotiating, and justifying their GN&C stability, performance, and V&V requirements. In many case flight projects simply opt to adopt and adapt legacy GN&C requirements previously used at their Center on other projects. The establishment of a single consistent set of fundamental GN&C guidelines would provide common NASA framework for future GN&C system development projects, tailorable to various vehicle and mission classes.

NASA, in the form of the NESC GN&C TDT, should initiate the development of a top-level guidelines handbook for the GN&C system DDT&E process. This effort could build upon work already performed by NESC for the Astronaut office at Johnson Space Center on human rated space system DDT&E engineering considerations. The TDT would leverage all available documented GN&C recommended practices currently used at the Centers. These would included the GSFC “Golden Rules”, the JPL Flight Project Practices, the MSFC launch vehicle design guidelines, and other such ‘best practices’. Those existing Center guidelines/requirements would be used, along with the initial set of NESC-identified GN&C Best Practices, as starting point for the NASA GN&C recommended best practices handbook. This handbook should also address several relevant topics, issues and concerns that have emerged from multiple NESC assessments, such as:

- Different GN&C terminology across the Centers
- Model uncertainty quantification methods (including the interpretation and application of NASA-STD-7009)
- Definition and quantification of stability and performance metrics
- Similarities and differences between GN&C design and development process across the Centers on different vehicle types/mission classes
- Model Verification and Validation as well as "Flight Certification" requirements and approaches for crewed spacecraft

IV. A Renewed Emphasis on Technology Development at NASA

Obviously, no one has a crystal ball to predict the future of the GN&C discipline within NASA. Making such predictions is particularly challenging given all the profound changes currently unfolding at NASA . It is however fair to assume that in the next few years the GN&C discipline within NASA will most likely remain stable and may in fact prosper with the investment in the development new technologies. Opportunities for innovative GN&C system development for robotic spacecraft will likely increase with growing demands for Earth and Space Science spacecraft as well as new robotic precursor vehicles. The challenge of designing and developing a new GN&C system for the planned Orion Emergency Rescue Vehicle is on the horizon as well. There is also high potential for new funding for GN&C technology development and in-space demonstrations of both AR&D systems and APL systems.

A new FTD Program is currently being planned to demonstrate the key technologies NASA needs to reduce the cost and expand the capability of future space exploration activities. Large-scale on-orbit demonstrations of technologies that could be transformational will be performed. The demonstration of AR&D is a primary objective of the FTD Program. AR&D is the ability of two spacecraft to rendezvous, operating independently from human controllers, and without other back-up; and requires advances in sensors, software, and real-time on-orbit positioning and flight control, among other challenges. This GN&C-based technology is critical to the ultimate success of capabilities such as in-orbit propellant storage and vehicle refueling/servicing (e.g. the development of space based fuel depots and servicing platforms).

These AR&D technologies will support not only NEO rendezvous but would enable efficient in-orbit space platform assembly operations in LEO. Initial investments should be made to mature the four critical component subsystem technologies which are specialized AR&D guidance and control realtime algorithms/flight software, relative navigation sensors/algorithms, docking mechanisms, and AR&D mission management software. Although NASA's Space Shuttle, DARPA's Orbital Express, US Air Force XSS-11, and other GN&C development efforts have advanced the technological state of the AR&D guidance and control algorithms to a very high level there is much work yet to do. The development, integration, ground test and flight test of algorithms into a modular realtime flight software architecture that can be tailored to suit the autonomy/automation requirements of various human or robotic spaceflight mission applications must be completed. In addition, a scalable spacecraft 'mission manager' software executive that can be tailored for various mission applications and levels of autonomy and automation is needed to ensure safety and operational confidence in AR&D software execution. Relative navigation sensors that can measure, with varying accuracy, bearing, range, and relative attitude will be needed for AR&D. Investments will be needed to mature the current mid-TRL optical, laser, and radio frequency (RF) relative navigation technologies and to obtain sufficient flight experience to demonstrate reliable performance and gain operational confidence.

The ETDD Program is also currently being planned to develop and demonstrate prototype systems to feed the Flagship Technology Demonstrations, robotic precursor, and other missions of opportunity. The ETDD Program will develop long-range critical technologies to provide the foundation for a broad set of NASA's future exploration capabilities. It will also provide infusion paths for promising, game-changing technologies developed by NASA's Space Technology Program. One key question the ETDD Program will attempt to answer is the following: How can we land autonomously, precisely, and safely on an extra-terrestrial surface in uncertain environments? An APL demonstration will be performed under this new Program to test an integrated GN&C-based autonomous landing and hazard avoidance system consisting of imaging sensors together with navigation and control algorithms. NASA plans to develop an atmospheric flight experiment to demonstrate an APL and hazard avoidance system on a small lander testbed. NASA would pursue use of this system on a U. S. or international robotic precursor mission to the Moon or other planetary body around 2015.

This APL work, similar to the AR&D work, promises to significantly advance NASA's GN&C capabilities opening up many new crewed and robotic mission applications. This new era in human exploration will challenge the persistence, flexibility, ingenuity and innovation of the GN&C CoP. Clearly as NASA changes direction over the next few years, we must maximize retention of the GN&C skilled personnel, from within NASA and its industry partners that can contribute to future technology developments such as AR&D and APL.

The development of groundbreaking new GN&C technologies, including AR&D, APL and others, will serve to enable exploration of new worlds and increase our understanding of the Earth, our solar system and the universe beyond. The GN&C CoP will need to be flexible and responsive to the many coming changes. For example, we will be pressed to find new collaborative ways to exploit the ISS to increase NASA's return on investment by providing an optimal on-orbit test bed for GN&C technology R&D. In order to accomplish our future goals we will need cross-Agency GN&C collaborations to continue and to improve and not suffer with Centers competing against each other under the stresses of moving forward with new NASA direction.

There are other forthcoming fundamental changes to the way NASA has been doing business for over a generation, which must be accommodated by the GN&C workforce. One is the imminent end of the SSP in FY11. Another is the proposed Commercial Crew Initiative. These two major changes are inter-related. The closeout of the SSP has the potential to impact the NASA GN&C workforce, particularly at those Centers that are focused on Human Spaceflight missions. We must guard against any erosion in GN&C capabilities following the Space Shuttle retirement. The skills of the highly experienced GN&C hardware and software specialists, who currently provide system integration and sustaining engineering functions for the Space Shuttle, will be critical to NASA's plans for developing the Orion Emergency Rescue Vehicle and for providing insight/oversight functions in support of the Commercial Crew Initiative. The Commercial Crew Initiative objectives are to facilitate the development of a U. S. commercial crew space transportation capability with the goal of achieving safe, reliable, and cost effective access to and from low Earth orbit and the ISS. Therefore, when the plans being formulated now are implemented, if and when authorized by Congress, there will be a stronger reliance by NASA on the commercial providers from industry to develop a safe, reliable space vehicle. A NASA insight/oversight approach is currently envisioned that will require a change in the way NASA and industry interact for human spaceflight missions. The goal is for NASA to have in-depth insight of the vehicle design through NASA personnel who are embedded in the contractor's facility while simultaneously maintaining a more traditional higher-level oversight role of the contractor's work. It is reasonable to assume a future demand will be placed on NASA's GN&C engineers to assume the responsibility for insight/oversight roles in support of the Agency's new direction towards utilizing commercial crew services. All these developments will no doubt place a strain on the GN&C workforce as NASA moves out in these bold new directions highlighted above. However, the GN&C discipline at NASA currently is mature, stable, healthy, and well poised to meet the challenges of the Agency's future.

V. Conclusions

This paper has presented the GN&C SoD. The GN&C discipline at NASA has been shown to satisfy the engineering needs and requirements of all four Mission Directorates.

As mentioned above the GN&C discipline at NASA currently is healthy and well poised to meet the challenges of the Agency's future. The GN&C CoP has done a great deal of collective learning in the past few years. Fortunately, in the Human Spaceflight arena, the CxP has provided multiple challenging learning opportunities for the next generation of GN&C engineers. Very positive cross-Center collaborations, , have occurred during the Orion spacecraft GN&C system design process, the Ares-1X, and Ares-1 launch vehicle flight control system design process and the Orion LAS design process. Likewise having multiple robotic spacecraft under development at JPL and GSFC has provided GN&C engineers at those Centers outstanding learning and development experiences. However, now, with so much change occurring within NASA and new challenges emerging it will be important to monitor and track emerging trends and dynamics within the GN&C CoP.

In addition to providing a current snapshot of the GN&C discipline at NASA this paper has also identified several GN&C engineering and technology challenges and critical GN&C needs, for which investment have been lacking over the years. In particular three key GN&C challenge areas were discussed in this paper. The first challenge had to do with the fact that advanced GN&C capabilities are not being exploited as much as they could be due to perceived risk of implementation. The second challenge concerned the lack of meaningful investments in the next generation of GN&C component-level technologies. The third challenge arises from the lack of consistent Agency-wide top-level guidelines for GN&C system DDT&E. Specific steps, many involving the efforts of the NESC GN&C TDT, to mitigate those challenges were recommended.

In summary, NASA decision makers should consider making sustained investments in the development, integration, and in-space demonstration of the following GN&C technologies:

- Formation Flying GN&C sensors, actuators, mission design tools, ground validation testbeds, and on-orbit technology demo opportunities for multi-spacecraft science applications.
- Autonomous rendezvous and docking systems, sensors, algorithms and ground validation testbeds and on-orbit technology demonstration opportunities.
- Adaptive flight control systems that respond to changes in operational environments and/or time-varying vehicle changes and/or commanded vehicle reconfigurations. This fundamental work to develop adaptive control systems and the methods to reliably validate their behavior prior to flight can be applied to all classes of NASA aerospace vehicles: aircraft, balloons, UAV's, launchers, piloted spacecraft, and robotic spacecraft.
- Ultra-accurate gravimetric sensors and systems for measuring planetary structures and natural resource monitoring.
- Ultra-precision Disturbance Reduction System (DRS) system technology supported by DRS sensor, algorithm, and actuator development
- Advanced control system technologies, integrated with advanced communications and command technologies, that enable new generations of safe and reliable Human-Robotic Systems which expand operational capabilities in extremely challenging space environments.
- Optical (laser) based systems for deep-space ranging applications with performance levels < 10cm accuracy. Such optical tracking technologies would complement the legacy Deep Space Network (DSN) functions and offer additional advantages such as increased accuracy and the possibility of 3-D ranging in which the three position elements of the state vector may be determined simultaneously.
- Autonomous multi-function modular GN&C with highly integrated fault management for deep space, planetary and NEO exploration.
- Miniaturized, low-power GN&C sensors for increased piloted or robotic spacecraft safety and reliability and as enablers for microsat/nanosat missions. The application of microtechnologies and nanotechnologies , together with Ultra-Low Power (ULP) electronics, will significantly impact many aspects of space system GN&C, especially as these technologies contribute to reduced mass and volume and the associated reduction in overall costs.
- Reliable long-life GN&C actuators such as advanced spacecraft reaction/momentum wheels (and CMG's for highly agile vehicles) as well as advanced in-space secondary propulsion for spacecraft.
- Precision telescope pointing, acquisition and tracking for both science applications and optical (laser) communications system applications.
- Autonomous air traffic management technologies and system concepts for maximizing utilization of the national airspace.

Lastly the critical need for multiple, low cost and routine flight test opportunities to demonstrate and validate emerging GN&C technologies cannot be overstressed nor overlooked. In particular the NASA GN&C CoP should carefully study and investigate methods to exploit the ISS as an on-orbit technology validation laboratory.

Acknowledgments

The authors would like to thank the GN&C Technical Discipline Team and GN&C line managers who have provided content for and feedback on this paper. Lastly, the author would also like to thank Scott Glubke (the GSFC Code 590 Chief Engineer) for his thoughtful review of and commentary on this paper.

References

[1] "Final Report: Review of US Human Spaceflight Plans Committee", N. Augustine (committee chairman), October 2009

[2] "Control in an Information Rich World – Report on the Panel on Future Directions in Control, Dynamics, and Systems ", R. M. Murray (panel chair), AFOSR document, 30 June 2002

[3] "Fundamental Aeronautics- Hypersonics Project - Reference Document", J. Pittman, P. Bartolotta, and N. N. Mansour, 25 May 25 2006

[4] "NESC Independent Assessment of the Constellation Program Preliminary Design Review", April 8 2010

[5] "Observations on the State of NASA's GN&C Engineering Discipline: Results of an Independent Non-Advocate Study", G. J. Pawlikowski and C. J. Dennehy, AIAA GN&C Conference and Exhibit, 5 August 2010, Toronto, Ontario, Canada (to be published).

[6] "Smarter Buyer 1: Industry Perspective", The Aerospace Institute Course S4350, The Aerospace Corporation, Chantilly, Virginia, 6 April 2010

[7] "Reference is Space News, 2/15/2010 by Turner Brinton, http://spacenews.com/military/100215-parts-problems-still-plaguing-space-missile-hardware.html