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GN&C Engineering Lessons Learned from Human Space Flight Operations Experiences

by

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Abstract

Documenting and sharing GN&C lessons learned helps the entire community of practice, including design engineers, test engineers, system engineers, flight operations engineers and project managers. Capturing and disseminating these GN&C lessons serves to minimize project risk and improve performance of system performance, operational reliability, and safety. The importance of identifying, documenting and widely sharing GN&C lessons learned during system design and development is broadly acknowledged by most aerospace engineering organizations. This paper addresses a recently observed concern. While NASA and other national spaceflight organizations do a reasonably good job of capturing the lessons learned arising from the GN&C system design and development phases of the project life cycle we are not so adept at identifying and capturing lessons learned from the flight operations phase of a given mission's life cycle. Often significant lessons learned during flight operations fail to be captured even though they are well known 'tribal knowledge' amongst the flight operations team members. This paper summarizes the results of a study performed by members of the NASA Engineering and Safety Center (NESC) Guidance, Navigation, and Control (GN&C) Technical Discipline Team (TDT) to systematically and comprehensively identify and document GN&C lessons learned that have emerged from NASA's human and robotic spaceflight operational experiences. We believe that some of these operational lessons learned can provide valuable feedback not only for the next generation of GN&C flight operations engineers but also for those engineers performing the up-front N&C design and development work.

Introduction

The importance of identifying, documenting and widely sharing Guidance, Navigation and Control (GN&C) lessons learned identified during the system design and development phases of a project life cycle is broadly acknowledged by most aerospace engineering organizations such as NASA and ESA. Documenting and sharing lessons learned helps both GN&C discipline engineers, system engineers, and project managers to minimize project risk and improve performance of their systems. Often significant lessons learned on a project fail to be captured even though they are well known ‘tribal knowledge’ amongst the project team members. The physical act of actually writing down and documenting these lessons learned for the next generation of NASA GN&C engineers fails to happen on some projects for various reasons.

The fundamental importance of being a learning organization has been clearly emphasized by both the NASA Chief Engineer and the NASA Chief of Safety and Mission Assurance (S&MA) in a letter directive to the NASA Center Directors as well as the Engineering Directors and the S&MA Directors at all the NASA Centers. In their letter Mike Ryschkewitsch and Bryan O’Connor, state the following:

> *“We are writing to request your active participation in addressing an issue of critical importance to the long-term health of NASA. NASA makes significant investments in the intellectual capability of our workforce, but all too often we do not make time available to capitalize on these investments. Our technical workforce possesses a depth and diversity of expertise that is second to none in the world, yet we leverage only a fraction of our capacity to share our knowledge and lessons learned with each other. At the senior leadership level, we trust that grassroots efforts will take care of this, but we do not expend enough personal effort supporting these activities from the top. This is not a new concern. In 2003, the Columbia Accident Investigation Board concluded that “NASA’s current organization…has not demonstrated the characteristics of a learning organization. Many high reliability organizations wrestle with this issue. The recent news about the "Spirit of Kansas" B-2 stealth bomber crash, where a technique learned by some flight and maintenance crews but not others probably would have prevented the accident, is a dramatic reminder that knowledge sharing is not "nice to do” — it is "must do."*

Ryschkewitsch and O’Connor go on in their letter to encourage the senior management and technical leadership within NASA to institutionalize the learning process within their organizations and to and to take the initiative to improve NASA’s performance as a learning organization.

This paper addresses a recently observed concern in this area that is limiting NASA’s ability to be as full a ‘learning organization’ as it could be. While NASA, and other national spaceflight organizations, do a reasonably good job of capturing the lessons learned arising from the GN&C system design and development phases of the project life cycle we are not so adept at identifying and capturing lessons learned from the flight operations phase of a given mission’s life cycle. Often significant lessons learned during flight operations fail to be captured even though they are well known ‘tribal knowledge’ amongst the flight operations team members. This paper summarizes the results of a study performed by members of the NASA Engineering and Safety Center (NESC) Guidance, Navigation, and Control (GN&C) Technical Discipline Team (TDT) to systematically and comprehensively identify and document GN&C lessons learned that have emerged from NASA’s human and robotic spaceflight operational experiences. We believe that some of these operational lessons learned can provide valuable feedback not only for the next generation of GN&C flight operations engineers but also for those engineers performing the up-front N&C design and development work.

Background

The National Aeronautics and Space Administration (NASA) Engineering Safety Center (NESC) was initially formed in July of 2003 in the wake of the Columbia tragedy. After 9 years of operation and after having completed over 400+ technical assessments the NESC has become the “value added” independent technical organization for the Agency. NESC is an independently funded NASA program whose dedicated team of technical experts coordinates and conducts objective engineering and safety assessments of critical, high risk projects. The NESC is a strong technical resource for customers and stakeholders seeking responsive service for solving the Agency’s difficult problems. NESC’s strength is rooted in the diverse perspectives and broad knowledge base that add value to its products, affording customers a responsive, alternate path for assessing and preventing technical problems while protecting vital human and national resources. NESC provides timely technical positions to its customers and stakeholders based on independent test and analysis, not opinion.

By encouraging alternative viewpoints and ensuring objective reporting methods, NESC is able to serve as a uniquely unbiased assessment resource. NESC’s technical evaluation and consultation products are delivered in the form of written reports that include solution-driven, preventative, and corrective recommendations. The NESC communicates its Lessons Learned from each assessment to NASA’s leadership through bi-annual briefings and to engineers through both the Agency Lesson Learned system and a series of NESC Technical Bulletins issued periodically. These communication channels function to inform the NASA technical community and, therefore, NESC’s customers and stakeholders. NESC’s range of services includes testing, analysis, and data review in fifteen engineering disciplines. NESC also engages in proactive discipline advancing activities.

The Guidance, Navigation, and Control (GN&C) Technical Discipline Team (TDT), the primary subject of this paper, is one of fifteen (15) such discipline-focused teams within the NESC organization. It is formed, maintained and led by the NASA Technical Fellow for GN&C. The TDT membership is composed of senior GN&C engineers from across NASA’s Field Centers as well as from its partner organizations in other government agencies, industry, national laboratories, and universities. Reference [1] provides a detailed description of the GN&C TDT including an overview of how this NESC team operates and engages in its objective engineering and safety assessments of critical NASA projects. References [1] and [2] both provide a summary of the GN&C TDT’s experiences performing a wide variety of NESC assessments and consultations.

Why Capture Lessons Learned?

In a time where NASA has limited human space flight launches in the next few years, it is imperative to capture the lesson learned through guidance navigation and control in human exploration. These lessons learned can be from human exploration and robotic mission that have value added G&NC lessons learned. These lessons learned can come from the Apollo, Shuttle, and International space station programs. By, doing this it helps to teach and train the future G&NC engineers who will work on the next major NASA program initiative. Effective knowledge capture and management during the DDT&E phase can reduce risk and increase the likelihood of mission success during the flight phase.

Ensuring safety and mission success depends on development, verification, performance analysis, and maintenance of hardware and software in on-board systems, ground systems, and ground facilities. Extensive analysis is performed in support of mission design, procedure development, and hardware evaluation. These activities require insight into underlying theory, requirements rationale, analysis techniques, systems performance and modification history, and software tools over the life of a program. The motivation to write this paper and the knowledge capture initiative was based on experiences with Shuttle Program corporate knowledge loss and difficulties encountered during the Orion Program with technical history research into Apollo and the Space Shuttle. Some of the reports were written for internal knowledge capture and training, other were written to transmit lessons learned and experiences to external audiences, and other reports and document compilations were created during the knowledge capture efforts near the end of the Space Shuttle Program.

An example of a recent process of capturing and documenting some “lost” GN&C lessons learned is given in Reference [3].

As part of the team of the GN&C technical discipline team for the NESC, it is the job of the team to help further the cause of having good designs of future GNC systems. Below is a list compiled by the discipline team of potential GN&C-related pitfalls that will threaten a successful space mission. Some of most common such pitfalls are listed below, with those occurring during, or directly related to, the operational phase highlighted in bold:

- Poor or Missing GN&C Requirements
- Failure to Stop Requirements Creep
- **Poor Characterization of Mission Operational Regimes & Environments**
- Inferior Architecture Development
- **Unknown or Poorly Defined Interactions**
- **Unknown or Poorly Defined Interfaces**
- Poorly Defined Coordinate Frames and System of Units
- Unknown and/or Incorrectly Modeled Dynamics
- Feedback Control System Instabilities due to Large Model Uncertainties
- Reliance on Any “Heritage”: in the Hardware, Software, Design Team, etc.
- Reliance on low Technology Readiness Level (TRL) GN&C technologies
- **Sensor/Actuator Component Degradation & Failure**

- Insufficient On-Board Processing Capability for GN&C Flight Software (FSW) Algorithms
- **Poor GN&C Fault Management Strategy**
- **Lack of Comprehensive Abort Strategy**
- **Inadequate "Safe Haven" capabilities**
- Failure to "Design for Test"
- Failure to "Test as You Fly"
- Inadequate Hardware In The Loop (HITL) End-to-End Testing to Verify Proper Operations
- Inadequate Sensor-to-Actuator Polarity Tests (Lack of End-to-End Testing)
- Unresolved Test Anomalies & Discrepancies
- No truly independent Verification and Validation (V & V) process for GN&C
- **Failure to "Fly as You Test"**
- **Failure to Have Crew and Operations Team "Train as You Fly"**
- **Inadequate Validation/Certification of GN&C Ground Data and Tools**
- **Insufficient Telemetry for GN&C Performance Monitoring and Anomaly Resolution During Launch, Early**
    - **On-Orbit Checkout & All Mission Critical Events**

This list is a perfect of example of why sharing GNC lessons learned is important for human space flight missions in the future for NASA.

NASA's Human Spaceflight GN&C Lessons Learned

Lessons from Early Crewed Mission Operations: Gemini and Apollo

The Apollo program was the third human spaceflight program carried out by the National Aeronautics and Space Administration (NASA), the United States' civilian space agency. Conceived during the Presidency of Dwight D. Eisenhower as a follow-on to Project Mercury, which put the first Americans in space, and Project Gemini, which developed the space travel techniques needed, Apollo succeeded in landing the first humans on Earth's Moon in 1969 through 1972. Apollo began in earnest after President John F. Kennedy proposed the national goal of "landing a man on the Moon and returning him safely to the Earth" by the end of the 1960s in a May 25, 1961 address to Congress.

Apollo ran from 1961 to 1972, and was supported by the two-man Gemini program which ran concurrently with it from 1962 to 1966. Apollo used Saturn family rockets as launch vehicles. Apollo / Saturn vehicles were also used for an Apollo Applications program which consisted of three Skylab space station missions in 1973–74.

The first moon landing was preceded by a series of spacecraft systems and mission technique demonstration flights that exercised capabilities during the various flight phases. From a mission profile standpoint, the ramp-up divided Apollo missions into three major categories: unmanned Earth orbit missions, manned Earth orbit missions, and manned lunar missions.
Apollo Flights 1 through 6 were unmanned suborbital and orbital flights that tested the launch vehicles, onboard systems, and the ground tracking network]. Apollo 7 was the first manned Apollo mission that included a 10.8-day orbital flight to test CSM systems and crew procedures. The first trip to the moon was performed during Apollo 8 but no landing took place as only the CSM was flown. It was a circumlunar flight that was the first manned mission to use the Saturn V rocket. Apollo 9 was a manned Earth orbit flight that flew all Apollo hardware and performed a successful LM rendezvous with the CSM. The next flight, Apollo 10 evaluated LM performance by descending to within 15,000 meters of the lunar surface. Apollo missions 11, 12, and 14 through 17 conducted successful manned lunar landings.

One of the most fundamental lessons learned early in the NASA Human Space Flight Program is the need to ensure the crew members train on a dedicated real-time spacecraft GN&C simulator facility. These simulators must be developed and maintained to allow the crew to realistically train and rehearse GN&C operations in the manner that they expect to actually fly the spacecraft. This “Train as You Fly” concept is at the heart of safe and reliable spaceflight operations.

From the early phases of Project Mercury through the Gemini and Apollo Programs, flight simulators have been the key elements in the astronaut training programs. As the missions progressed in complexity, the sophistication, number, and variety of simulators employed for astronaut training were increased correspondingly.

It was necessary to evolve the fidelity of these manned spacecraft flight simulators to meet the escalating demands in crew training requirements. A review of the historical record shows that the Apollo astronauts relied much more heavily on spacecraft simulators than did the Gemini crews. There were three sets of these simulators developed (two at Kennedy launch site in Florida and one at the Johnson Manned Spacecraft Center in Houston) - modeled after the flight versions of the CM and the LM. The simulators, constantly being changed to match the cabin layout of each individual spacecraft, were engineered to provide the crew with all the sights, sounds, and movements they would encounter in actual flight. The Apollo crews would require about 180 training hours in the CM simulator plus an additional 140 hours in the LM simulator. This represented about an 80 percent increase in simulator training time as compared to what the astronauts on the early Gemini flights had required.

There were several key factors that emerged during the Apollo Program as critical and basic for providing adequate flight simulators for astronaut crew training [see Reference 4]. First among these are high-fidelity crew stations, especially in the area of GN&C flight controls and displays. Another was identified as the accurate simulation of the guidance computer and navigation systems. Others included complete visual display systems for simulated out-the-window scenes and certain moving-base simulators for high-fidelity training in particular portions of the missions. The significance of each of these factors for new programs will depend to a large degree on the mission objectives and requirements. One can unequivocally state however that these spacecraft flight simulators, incorporating significant GN&C attributes in their design and operations, will be vital in future astronaut training.

Astronaut “hands-on” involvement in the design and development of the GN&C systems and associated flight simulators is a must. Intensive training in a real-time functional simulator not only trains the crew in the operational aspects of the GN&C system but it also permits the crew to feedback information that will enhance safety, operational efficiency, and mission success.

The astronaut crews are the ultimate “stake holders” of the GN&C design. Too often, the designer implements a fully automatic implementation routinely used in unmanned robotic spacecraft. Astronaut interchange to define needed critical display monitoring, mode sequencing with intervention provisions, alternative procedures and abort provisions are extremely valuable. Current technology enables many operations to be implemented automatically and sequenced as nominally indicated in various mission phases. Methods to provide Astronaut assessment of satisfactory performance and means to implement work around provisions should be a design requirement.

On the Apollo Program, astronaut participation in both the CSM and LM implementation meetings identified architectural mode enhancements as well as display and other monitoring provisions. Use of mockups and realistic simulators enabled extensive crew training. Understanding and familiarity with the functionality and operation of the GN&C system proved invaluable in reestablishing operation of the system after a lightning strike during the Apollo 12 launch. Manual control provisions enabled the divert maneuver by Apollo 11 when the auto selected landing site was observed as being hazardous.

Participation in mock up reviews facilitates the human engineering process and enhances the design. Extensive real-time simulations were in place during Apollo and the Shuttle development and fielding. The Shuttle program included a Shuttle Avionics Integration Laboratory (SAIL) and Shuttle Motion Simulator (SMS) facility with real time operation and cockpit set-up. The SMS is used primarily for training and the SAIL is an engineering simulation that is open to Astronaut participation.

The real-time spacecraft simulator would support GN&C/Human interaction training for the crew in normal and contingency operations of the GN&C subsystem. The crew would be able to refine and practice GN&C operations and contingency procedures without using valuable spacecraft time. The spacecraft simulator could also be used to validate GN&C command/telemetry data flows between the spacecraft and the ground network.

The GN&C engineering models built into such a real-time simulator would also allow the Crew to have input into GN&C/Human interaction at an early design phase.

The GN&C simulator can be also used to support on-orbit operations, especially to checkout and validate new GN&C contingency procedures. The ability to implement alternate operational procedures and tests proved to be life saving in Apollo 13.

Lessons from STS Operations

For 30 years, NASA's Space Transportation System (STS), also known as the shuttle program, was the United States' launch vehicle for the human spaceflight program. With the last shuttle launch on July 8, 2011, NASA is exploring alternatives for future launch vehicles; attention to lessons learned during the shuttle program will serve NASA well in making its launch vehicle decision.

Johnson Space Center (JSC) is the center for human spaceflight training, research, and flight control. The daily operation of the space shuttle has been conducted at the JSC Mission Control Center (MCC-) in Houston, Texas. The main task of an MCC is to manage space missions, from lift-off until the landing or the end of the mission. Flight controllers, flight crew, and other support personnel provide real-time support of all aspects of the mission, including vehicle telemetry monitoring, commanding, mission planning, and trajectory design. MCC personnel include operations subject matter experts for the attitude control system, power, propulsion, thermal, attitude dynamics, orbital operations, and other subsystem disciplines.

The Mission Control Room

Before the space shuttle program began, the room where the flight controllers worked was called the Mission Operations Control Room (MOCR); for the last three decades it has been called the Flight Control Room (FCR). A description of the control room layout and the responsibilities of each participant set the stage for understanding the complexity of each subsystem role, the importance of effective flight controller training, and how the training is implemented in the human flight program (Reference 5).

The FCR has four rows of consoles; each console is dedicated to a specific area of expertise. Each console is labeled with an abbreviation that clearly identifies the responsibility. MCC seat assignments are shown in Figure 1; Table 1 describes controller roles and responsibilities.

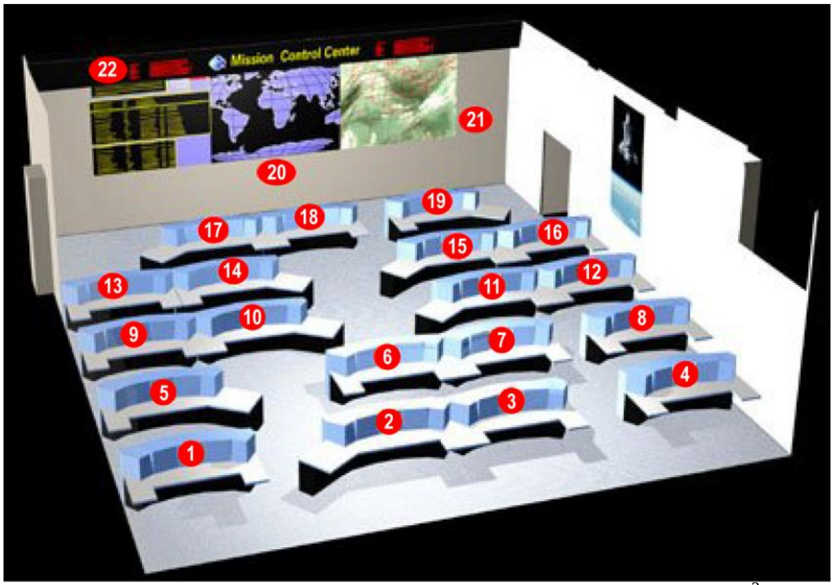

Figure 1:Console locations in the MCC are identified by number. [3]

1. Public Affairs Officer (PAO)
2. Mission Operations Directorate Manager (MOD)
3. Booster Systems Engineer (BOOSTER) and External Vehicle Activity Officer (EVA)
4. Surgeon (SURGEON)
5. Integrated Communications Officer (INCO)
6. Flight Director (FLIGHT)
7. Spacecraft Communicator (CAPCOM)
8. Payload Deployment and Retrieval System (PDRS)
9. Data Processing System Engineer (DPS)
10. Assembly and Checkout Officer (ACO)
11. Flight Activities Officer (FAO)
12. Electrical, Environmental, and Consumables Manager (EECOM)
13. Propulsion Engineer (PROP)
14. Guidance, Navigation, and Controls Systems Engineer (GNC)
15. Maintenance, Mechanical, Arm, and Crew Systems (MMACS)
16. Electrical Generation and Illumination Engineer (EGIL)
17. Flight Dynamics Officer (FDO) and Trajectory Officer (TRAJ)
18. Guidance and Procedures Officer (GPO) or Rendezvous (RNDZ)
19. Ground Controller (GC)
20. Worldmap Screen
21. TV Screen
22. Mission Clocks/Telemetry Data

Image courtesy of the National Aeronautics and Space Administration.

Every flight controller is a subject matter expert in his or her system and makes recommendations about the system to the flight director. Any controller may call for an abort if certain flight rules are violated or if circumstances require an abort to keep the crew and vehicle safe. Before major mission events (such as an on-orbit space burn) in the flight plan take place, the flight director "goes around the room" to poll each subsystem for a GO/NO-GO decision. If the subsystem is in good working order, the responsible controller calls for a GO, but if there is a problem in a subsystem, the responsible controller's call is NO GO, and the flight director holds or aborts the event.[2]

Space shuttle flight controllers work relatively brief periods, especially compared to their International Space Station (ISS) counterparts: the several minutes of ascent, the few days the vehicle is in orbit, and reentry. The duration of operations for space shuttle flight controllers is short and time-critical. A failure on a critical phase of the shuttle flight could leave flight controllers little time for decision making, so it is essential that they respond quickly to mitigate potential failures. The controller's ability to send commands to the shuttle for system reconfigurations is limited; if a reconfiguration is needed, then the desired configuration is relayed via the subsystem controller to the spacecraft communicator (CAPCOM) and then to the shuttle crew.

Flight controllers feel very responsible for the success of the mission and for the lives of the astronauts under their watch. There is a phrase often heard in the FCR: “Always be aware that suddenly and unexpectedly we may find ourselves in a role where our performance has ultimate consequences.”

Table 1. Mission Operations Control Room Team: Roles and Responsibilities During Flight.[3]

Role	Console Label	Position (cf Fig. 1)*	Responsibility
Assembly and Checkout Officer	ACO	10	Develops ISS assembly, activation and checkout operations, including the responsibility for any required integrated procedures. Coordinates these activities in real-time. Coordinates payload and transfer operations. Responsible for ISS visiting vehicle systems integration, safety, and all docked operations, including transfer operations, plans, procedures, and systems commanding and telemetry.ACO was formerly known as PAYLOADS.
Booster Systems Engineer	BOOSTER	3	Monitors and evaluates performance of propulsion-related aspects of the launch vehicle during prelaunch and ascent, including the main engines and solid rocket boosters.
Data Processing System Engineer	DPS	9	Responsible for data processing systems in a space flight. Monitors the onboard general-purpose computers , flight-critical launch and payload data buses, the multi-function electronic display system, solid-state mass memory units, flight-critical and payload multiplexer/de-multiplexer units, master timing unit, backup flight control units, and system-level software. The space shuttle general-purpose computers are a critical subsystem, and the vehicle cannot fly without them.
Electrical, Environmental, and Consumables Manager	EECOM	12	Maintains atmospheric pressure control and revitalization systems, cooling systems (air, water, and freon), and supply/waste water system. EECOM's critical function is to maintain the systems, such as atmosphere and thermal control, that keep the crew alive.
Electrical Generation and Illumination Engineer	EGIL	16	Monitors cryogenic levels for the fuel cells, electrical generation, and distribution systems on the spacecraft, as well as vehicle lighting. This is a portion of the job was formerly done by EECOM.

Role	**Console Label**	**Position (cf Fig. 1)***	**Responsibility**
Extravehicular Activity Officer	EVA		Responsible for all spacesuit and spacewalking–related tasks, equipment, and plans when the EVA takes place from the shuttle. The EVA officer shares a console with BOOSTER. EVA uses the console during the orbit phase of the flight.
Flight Activities Officer	FAO	11	Coordinates implementation of the flight plan and develops alternate and flight plans, as required. Provides the capability to transfer data (text, graphics, and video) between a ground PC network and the orbiter laptops.
Flight Director	FLIGHT	6	Provides overall management and authority for flight execution. Responsible for the detailed control of the mission, from prelaunch until post landing.
Flight Dynamics Officer	FDO	17	Responsible for the flight path of the space shuttle, both atmospheric and orbital. Monitors vehicle performance during the powered flight phase and assesses abort modes, calculates orbital maneuvers and resulting trajectories, and monitors vehicle flight profile and energy levels during re-entry. The FDO and TRAJ share a console in the MCC.
Ground Controller	GC	19	Directs maintenance and operation activities affecting MCC hardware, software, and support facilities. Coordinates spaceflight tracking and data network. Coordinates Tracking and Data Relay Satellite System with Goddard Space Flight Center.
Guidance and Procedures Officer	GPO	18	Depending on the phase of flight the mission is in, position 18 is either staffed by GPO (a specialist in the procedures related to flight or RNDZ (a specialist in orbital rendezvous procedures). GPO is responsible for monitoring the Shuttle guidance and navigation as well as execution of crew procedures, particularly for ascent abort situations.
Guidance, Navigation, and Controls Systems Engineer	GNC	14	Responsible for operating and monitoring the sensor system, which includes navigation sensors and associated software. Responsible for flight control system hardware and software, which includes aero and reaction control system controls, digital autopilots, main engines, solid rocket boosters, and orbital maneuvering system thrust vector control with associated software.

Role	**Console Label**	**Position (cf Fig. 1)***	**Responsibility**
Integrated Communications Officer	INCO	5	Responsible for all data, voice and video communications systems. Monitors the configuration of in-flight communications and instrumentation systems. Monitors the telemetry link between the vehicle and the ground. Oversees the uplink command and control processes. This position evolved directly from the Apollo program Integrated Communications Officer role.
Maintenance, Mechanical, Arm, and Crew Systems	MMACS	15	Responsible for space shuttle structural and mechanical systems. Monitors auxiliary power units and hydraulic systems. Manages payload bay door, external tank umbilical door, vent door, radiator deploy/stow, Ku-band antenna deploy/stow, and payload retention latch operations, landing gear/deceleration systems (landing gear deploy, tires, brakes/antiskid, and drag chute deploy).Monitors the orbiter docking system. Tracks use of onboard crew hardware and in-flight equipment maintenance. This represents a portion of the job formerly done by EECOM, with additional responsibilities added by the specific requirements of space shuttle operations. The MMACS officer serves as the point of contact for PDRS, BOOSTER, and EVA during periods in a mission when these positions do not require constant staffing.
Mission Operations Directorate Manager	MOD	2	Serves as an upper management interface to the flight operations team.
Payload Deployment and Retrieval System	PDRS	8	Responsible for space shuttle remote manipulator system, also known as "robot arm."
Propulsion Engineer	PROP	13	Manages the reaction control thrusters and orbital maneuvering engines during all phases of flight. Monitors fuel usage and propellant tank status. Calculates optimal sequences for thruster firings.
Public Affairs Officer	PAO	1	Serves as a liaison between the public information media and the flight operations team.
Rendezvous	RNDZ	18	Depending on the phase of flight the mission is in, position 18 is either staffed by GPO (a specialist in the procedures related to flight or RNDZ (a specialist in orbital rendezvous procedures). RNDZ is. responsible for activities such as trajectory operations related to the rendezvous and docking/capture with another spacecraft, including the Mir space station, ISS, and satellites such as the Hubble Space Telescope.

Role	**Console Label**	**Position (cf Fig. 1)***	**Responsibility**
Spacecraft Communicator	CAPCOM	7	Provides air-to-ground communication between the flight crew members and ground support team. Ensures that ground recommendations regarding vehicle maintenance and control are transmitted clearly and appropriately to the crew.
Surgeon	SURGEON	4	Provides real-time medical consultation on issues related to flight crew member health and safety.
Trajectory Officer	TRAJ	17	Assists the FDO during time-critical operations. Maintains the various processors that help determine the shuttle's current and potential trajectories. A controller who wants to become a flight dynamics officer must first be certified as a trajectory officer. The FDO and TRAJ share a console in the MCC.

GNC Space Shuttle Lessons Learned

Treatment of Ground/Mission Operations Databases and Tools

NASA’s human spaceflight flight operations experiences have shown the importance of treating GN&C ground/mission operations databases, uploads, ground application tools, command scripts/files etc. with the same disciplined care that the GN&C Flight Software code and data are treated.

The engineers who initially conceive and design a GN&C system often do not stay with the program through the flight operations phase. Consequently, the reasons behind the selection of certain parameters or operational procedures may not be apparent to spacecraft operators at a later time. Ad hoc changes in the databases or operational procedures can be fatal to the mission. Thorough training and adherence to the established procedures for ground software/database configuration management, documenting change history, version archiving, and peer review is essential for the flight operations team.

One should consider the following relevant questions:

1. Are command scripts formally controlled?

2. What is the procedure for establishing yellow caution and red alarm telemetry monitor limits? Is there an independent analysis of the values before flight?

3. What is the process to make changes in the GN&C databases?

4. Will the same GN&C Command and Telemetry system be used in Integration & Test as will be used for Flight Operations?

5. Under what operational circumstances must a GN&C system design engineer be notified?

6. Is there a document describing the type and extent of GN&C training that is provided to the flight operations team?

7. Does the GN&C System Design document explain in detail the rationale for the selection GN&C subsystem parameters and the operations procedures?

Adequate GN&C Telemetry

NASA's human spaceflight flight operations experiences have shown the importance of ensuring that sufficient GN&C engineering telemetry data is down-linked to diagnose anomalies, particularly during all mission critical phases including the early on-orbit operational period when many anomalies or failures tend to occur.

Anomalies occur in even the best of systems. The most important factor in resolving them is getting access to the right telemetry data. Having good data greatly simplifies diagnosis of the root cause of the anomaly and reduces the time required to correct it. The routine engineering telemetry that is available for evaluating normal operations is often inadequate to help resolve anomalies efficiently. Good diagnostic data typically includes many more variables and it is sampled at a significantly higher rate. Plans for providing sufficient diagnostic telemetry should be included in the initial designs of the GN&C and telemetry systems.

It is highly advisable to develop a set of ground displays for the GN&C engineers working launch and/or mission operations that will allow problems to be identified and diagnosed quickly. Ensure a dedicated real-time GN&C simulator is developed to allow these GN&C flight operations +engineers to realistically train and rehearse critical GN&C operations in the manner they expect during launch and/or mission operations.

One should consider the following relevant questions:

1. How many variables are in the telemetry lists for normal engineering data and diagnostic data? How many spare data slots are available?

3. What are the sample rates for normal engineering data and diagnostic data?

4. What plans are in place to continue to add to the GN&C H/W and S/W performance trend database that was collected during the I&T phase with similar on-orbit trend data?

5. What is the maximum angular velocity that the spacecraft might reach in the event of a worst-case anomaly? Is the data rate for the diagnostic telemetry high enough, and the data scaling appropriate, to unambiguously track the relevant parameters in that situation?

6. Is the diagnostic data taken and temporarily stored automatically or does high rate sampling have to be enabled by a command? How much diagnostic data can be stored on-board?

7. What is the adaptive capability of the spacecraft's telemetry system to capture non-routine GN&C engineering data in support of anomaly resolution? In particular, does the spacecraft's telemetry system provide capabilities for adding new GN&C telemetry points, collecting specific telemetry points (e.g., inertial sensor outputs) in a high data rate "dwell mode" manner, and to re-scale selected telemetry data points?

Recommendations/Conclusions

Basically we need to do a better job identifying, capturing, and dissemination GN&C lessons learned from the flight operations phase of a mission’s life cycle. The major item is for each program within NASA is to document GN&C lessons learned from the design phase of vehicles through its operation lifetime. This includes robotic and human space flight missions within NASA. By doing this activity, there will be a wealth of knowledge to refer to for commercial crew companies try to work on human space flight vehicles, and for NASA refer to when they return to regular human space flight. Below is a list of good practices identified over 50 years of spaceflight operations. NASA has found that many GN&C problems and issues can be avoided with a proactive multi-pronged approach that includes the following elements:

- Team wide emphasis on safety and mission success
- Open and clear communication across entire Project team
- Maintaining a systems-level perspective while working discipline-specific issues
- Rigorous failure mode analysis (including degraded/anomalous modes of operation)
- Formulating a common understanding of what can go wrong during the mission
- Contingency planning based on consequences of what can go wrong
- Formal risk analysis and trades
- Infusion of Lessons Learned
- Consideration and attention to Best Practices
- Holding independent non-advocate peer reviews

- Exploiting external expert knowledge and technical support when needed

References

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Author Biographies

Gary Dittemore

Gary Dittemore is currently serving in the International Space Station Chief Engineers Office at Johnson space Center in Houston, Texas. He has worked in constellation Integration Office in the Mission Operations Directorate on different telemetry requirements and systems engineering work. Recently, he worked as a Resident Engineer on the Max Launch Abort System for the NASA Engineering and Safety Center at Langley Research Center. He also serves as a propulsion systems console operator assigned to Propulsion System Group in the Mission Operations Directorate at JSC. He is responsible for real time on-console ground oversight and operations of the space shuttle orbital maneuvering system and the reaction control system. On-console responsibilities include procedure execution, flight activity planning and review, and anomaly response. He has supported eight shuttle flights as a certified propulsion systems console operator in the mission control room. His responsibilities also included managing flight systems operations duties for a spacecraft system both pre-flight and during human-staffed flight. Pre-flight activities involve systems hardware and software analysis, design, and testing. He developed real time support requirements, system operation procedures for flight control and flight crew in nominal and contingency situations, and validated these procedures through ground simulations. Mr. Dittemore graduated from the Brigham Young University with a BS in Mechanical Engineering in 2004. Mr. Dittemore is currently working on his Masters in Systems Engineering at the Stevens Institute of Technology in Hoboken New Jersey.

Neil Dennehy

Mr. Dennehy is the NASA Technical Fellow for Guidance, Navigation and Control (GN&C). Within the GN&C discipline he provides technical leadership for independent test and analysis, risk assessment and problem resolution for the Agency. Mr. Dennehy has over 30 years of experience in the design, development, integration and operation of GN&C systems for communications, national security, remote sensing and scientific platform applications. His technical emphasis has been in the areas of spacecraft attitude determination and control system design, system development, technology development, integration & test, and flight operations. Prior to joining NASA, Mr. Dennehy held engineering and management positions with several aerospace industry organizations including The Analytical Sciences Company (TASC), Fairchild Space Company, EOSAT, Welch Engineering, and Draper Laboratory. Before joining the NESC organization he was the GN&C Technologist at Goddard Space Flight Center where he directed a portfolio of diverse technology developments for NASA's Earth and Space science missions and instruments. He is the author (or co-author) or over twenty-five technical papers on GN&C, spacecraft, or related aerospace-related topics. Mr. Dennehy contributed chapters to the "MEMS and Microstructures in Aerospace Applications" textbook providing both a broad vision for future microtechnology space missions and specifics on Microsystems for spacecraft GN&C applications.
