Gateway Avionics Concept of Operations for Command and Data Handling Architecture

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Abstract—**By harnessing data handling lessons learned from the International Space Station, Gateway has adopted a highly reliable, deterministic, and redundant three-plane Time-Triggered Ethernet network implementation that is capable of handling three distinct types of traffic: Time-Triggered (TT), Rate Constrained (RC) and Best Effort (BE). This paper will offer an overview of the operational capabilities of the Gateway Network defined in the Network Concept of Operations, focusing on the initial architecture of the Gateway Spacecraft Inter-Element Network. The initial Gateway modules include Habitation, Power & Propulsion, Logistics, Human Lunar Lander, and Orion Crew Capsule. The Gateway Inter-Element Network Concept of Operations is a source for the network functions, which in turn inform the design, development, implementation, testing, and verification of the spacecraft hardware. End system hardware on the network includes, but is not limited to, a mobile robotic arm, internal and external cameras, flight control hardware, environmental control systems, power and propulsion systems, critical alarms, telemetry, and payloads, in addition to any hardware present on a visiting vehicle or lunar exploration vehicle. This paper will also provide an overview of how the design and operations of the Gateway Avionics network are defined by the Gateway Program design and safety requirements. Implementation of avionics and command and data handling strategy will provide the Gateway program with reliable infrastructures that allow operational options for both human control while occupied, and highly autonomous control during periods of vacancy. The Gateway Avionics network architecture will be able to handle seamless in-flight reconfigurations and expansion as new modules and the capability to interface with additional visiting vehicles are added.**

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1. INTRODUCTION

With NASA, international partners, and commercial partners preparing to establish a human presence in lunar orbit, a robust implementation of avionics is of the utmost importance to the Gateway Program's success. Without technological advances in C&DH, previous missions would not have been possible. Previous lessons-learned with ISS will help shape the design philosophy of the network architecture used in the Gateway Program.

2. ARCHITECTURE

Distributed Integrated Modular Avionics (DIMA)

From well into the Shuttle program, discrete flight computers were used to perform various avionics functions. As technology progressed, NASA moved towards a Distributed Integrated Modular Avionics (DIMA) architecture [1]. By utilizing common flight computers to perform various tasks, several benefits are realized. A reduction in cost, weight, and design complexity is found, interchangeable common components leads to an increase in maintainability, and finally the capability to build-up the spacecraft while on orbit is attained. However, these gains are not without consequences. The additional complexity of prioritizing multiple functions within each computer arises, and more importantly, prioritizing traffic on the inter-element network must be dealt with as well.

Inter-element Network Interfaces

The Gateway consists of an Inter-element network backbone of 3-planes and switches that transgresses rectangle umbilical connectors of RUCs that dock elements together. The initial phase consists of the power propulsion element (PPE) and the Habitable Logistics Outpost (HALO). External science payloads connect through Small ORU Interfaces or SORIs. Internal payloads will interface to the inter-element switches in payloads racks similar to the International Space Station [2]. A robotic arm connects via a Low-Profile Grapple Fixture or LPGF. Internal and external wireless devices also

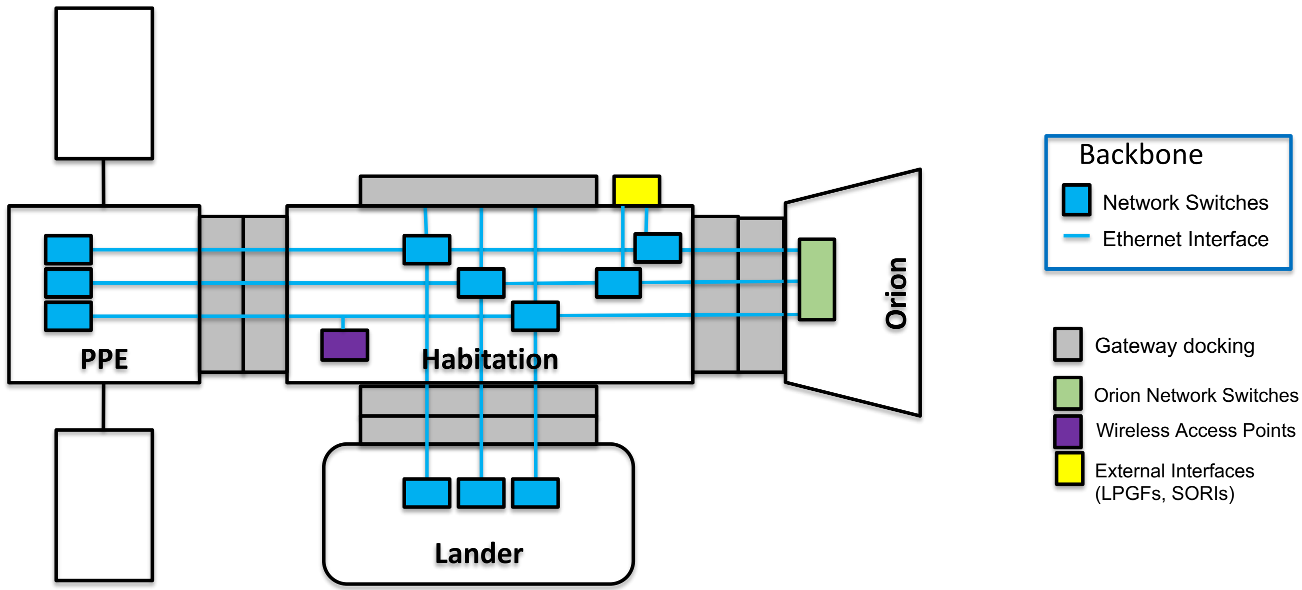

Figure 1. Interface Architecture for Lunar Gateway

interface with the inter-element network backbone. This is shown in Figure 1.

Three distinct traffic types (TT, RC, BE)

To accommodate the necessary traffic prioritization on the Gateway Inter-Element Network, three distinct traffic types coexist. The highest priority belongs to Time Triggered (TT) ethernet following the SAE AS6802 standard for time triggered synchronization protocol. The second priority tier is Rate Constrained (RC) ethernet following the ARINC 664 standard. Any bandwidth not consumed by TT or RC is available for Best Effort (BE) traffic following the IEEE 802.3 standard. This priority scheme allows avionics operations to be efficiently and effectively scheduled based on pre-determined criticality levels, thus ensuring temporal or spatial functions occur as intended while allowing non-critical functions to proceed as bandwidth availability allows [3].

To facilitate Time Triggered Ethernet, connected devices must be capable of synchronizing to a shared base time. This is accomplished by classifying devices as either a Synchronization Master (SM), a Compression Master (CM), or a Synchronization Client (SC). The SMs on the network transmit a specific packet called a Protocol Control Frame (PCF) which are received by all CMs. The CMs then calculate the synchronized network time and transmit new PCFs which are ingested by all other devices on the network and averaged with other CM PCFs. This process is repeated periodically to ensure all network devices maintain the same synchronization clock. The PCF traffic and synchronization process generates additional processing workload for all TTE devices attached to the network [2].

Time Triggered traffic operates on a specific schedule while utilizing pre-defined paths called Virtual Links, which must be specified in the network scheduler. TTE packets are nearly identical to 802.3 Ethernet packets, with one crucial alteration. The 6 bytes containing the Destination Address are replaced with a 4-byte Critical Traffic (CT) Marker and a 2-byte Critical Traffic Identifier (CTID) [3]. To any non-TTE device, these 6 bytes appear to be a MAC address. TTE devices recognize the CT Marker to denote TTE traffic, and the CTID as the indication of which VL to use for the packet. Any connected routers, switches, or network interface cards must contain hardware or software capable of recognizing the CT and CTID to allow appropriate delivery of the packet to its intended destination at the allotted time. This per-packet capability to transfer data on a specific path creates an additional computation to be performed, further increasing network overhead.

While TTE traffic is best suited for data that is continuously monitored, and can therefore be scheduled, there is also a need to ensure certain unscheduled data is readily available. Rate Constrained traffic is an event driven rather than schedule driven QoS enhancement that also utilizes VLs to transmit data. RC frames are allocated in the space between TT frames. Like with TT, RC packets replace the Destination Address with a CT Marker and CTID [4]. Further processing overhead is required to recognize RC frames and ensure they do not exceed the available Bandwidth Allocation Gap (BAG) and intrude on TT traffic. If a RC frame surpasses the BAG, it will be silently dropped by the switch.

Best Effort traffic utilizes the bandwidth left over after traffic of the two higher priorities is transmitted and can take any path between the sender and receiver that happens to be available [5]. No additional overhead is required for BE traffic, however with the processing requirements for the previous two traffic classes, the ability to maintain maximum data throughput for the entire network is diminished, thereby lowering the availability for all classes.

Three Plane Ethernet Structure

In order to meet the expected reliability, safety, fault tolerance, and fault containment requirements necessary for Human Space Exploration, the Gateway will be equipped with three redundant network planes. By allowing traffic to propagate across three separate network planes, dual-fault tolerance to network failures is ensured for any End System connected to all three planes [6]. Furthermore, by mirroring End System communications across three planes, an additional layer of fault tolerance is introduced by allowing End Systems to implement one of two methods for frame usage selection. The device or application can either ingest all received frames then internally to select the frame to use, or it can simply use the first valid frame to arrive [7].

Highly reliable and scalable

The main vehicle processors can be cross-strapped with network switches for all 3-planes. Each processor will have connections to all three planes, while each switch can be plane independent. This plane isolation on network switches helps to isolate faults. An example of 3-processors cross-strapped to three switches is shown in Figure 2.

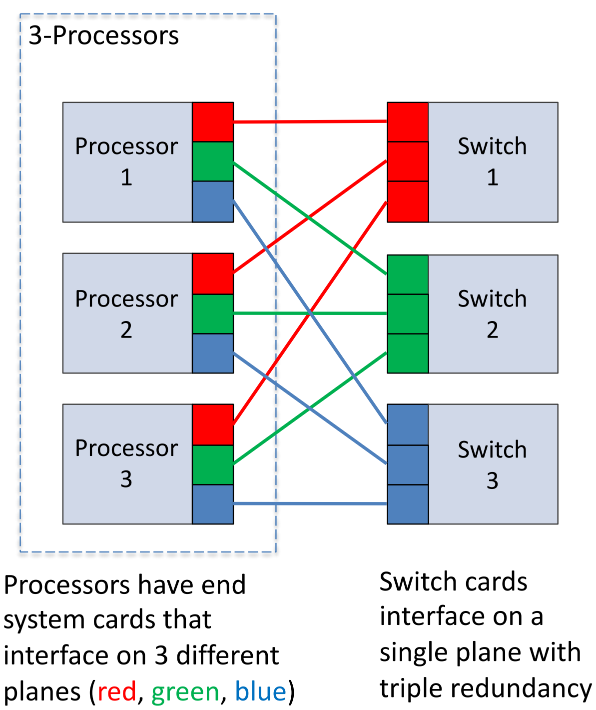

Figure 2. Multiprocessor to switch interfaces

When designing a spacecraft that operates using DIMA, network scalability is increased, but it becomes more difficult to construct a highly reliable network. By developing a network with tiered traffic priorities and multiple redundant planes, the Gateway Spacecraft is provided with a highly reliable and scalable network infrastructure [1].

3. Concept of Operations

Network Scheduling

The use of pre-defined Virtual Links creates a need for meticulous network design and scheduling. The scheduling is performed offline with tools provided by the hardware manufacturer for upload to the network as the system grows or is altered. This development method creates a unique opportunity to build the sought after reliable and scalable network. By planning and testing the network in a controlled environment prior to deployment to the in-flight spacecraft NASA establishes the capability to build the Gateway in phases, with additional modules or vehicles connecting to the network as the mission progresses [3].

Virtual Link Configuration

TT and RC frames both rely on VLs to route data from source to destination. VLs can be configured to one or many end systems but may only have one origination point. VL data is stored in all switches between the source and destination or destinations, on all three planes. This pre-determined path provides the capability to schedule TT traffic, as the time for a message to transit the network can be reliably determined due to the static routing VLs provide. The use of VLs also reduces the circulation of erroneous packets by traffic management policies. If a frame is received by a switch that is not scheduled in the devices forwarding table, the frame is discarded, thereby preventing errors from spreading through the network [6].

Naming Conventions

For a network to perform routing via a configuration table built by a Network Scheduler, a human-readable standardized naming convention is paramount to reduce the likelihood for errors.

End System Naming Convention

End Systems are identified by using the prefix ES, with a three-digit identification number. After ESxxx, the port speed is indicated with either a G for gigabit, or M for 100 megabits. The last segment of an End System name depends on the type of port used. Standard Ports are labeled 1, 2, or 3. Host Ports are labeled HOST, and Synchronization Ports are labeled SYNC. An example End System that is a Synchronization Master would be ES001_GSYNC [4].

Switch Naming Convention

Switches follow a similar convention to End Systems, with subtle differences. Switch names begin with SW and the two-digit unique identifier of the switch followed by the plane it operates in. The planes are identified as 0, 1, and 2 to follow the conventions used in tools. If the switch is an Internal End System, IES appears before the port speed identifier of G for gigabit or M for 100 megabits. Similar to the End System naming, the last segment depends on the port usage. A standard port is labeled 01 through 12 for flight, a

Synchronization Master is labeled SYNC, a Management Port is labeled MGMT, and a Host Port is labeled HOST. An example Switch Management Port would be SW01.0_MMGMT [5].

Network Interface Naming Convention examples

- Physical Link

Physical Links are used to identify the connections between ports made via traditional copper Ethernet cabling. Their names begin with PLINK followed by the Plane, then the ports of the two devices they connect to. An example would be PLINK_PL0_ES001_G1_SW01G01 [4].

- Virtual Link

Virtual Links are individually built by the network designer to create a unidirectional path between one transmitting End System and one or more receiving End Systems. Virtual Link names begin with VL followed by either TT or RC then a unique five-digit identification number. An Example would be VL_TT_00500 [4].

- Logical Link

Logical Links are like Virtual Links in that they are unidirectional paths between one source and one or more destinations, however a Logical Link is a method of assigning Virtual Links to ports. If the Logical Link is a sender, then only one Virtual Link can be assigned, if the Logical Link is a receiver, multiple Virtual Links can be assigned, even by using wild cards. Logical Link names begin with DPORT followed by the End System name from above. Next in the name is VL and the five-digit identification number assigned to the Virtual Link. Then there are two user-definable segments Domain and Description and finally either Send or Receive. An example Logical Link would be DPORT_ES001_VL00500_SCH_SYNC_SEND [4].

Auto Negotiation/Address Learning

The usage of Virtual Links and scheduling for TT and RC traffic negates the need for dynamic addressing on most traffic. In the event a BE device does not support static addressing, the switches can provide auto-negotiation on a per port basis. In addition to static addressing, BE devices will use static routing wherever possible. The few exceptions to this would be allowed for devices designed to be portable and therefore moved between ports as required by crew while in flight. Reducing the number of dynamic routed devices minimizes the potential for erroneous data to flood BE enabled ports [6].

Maintenance and Planned Reconfiguration

Operations in space present unique challenges for the planning and deployment of the Gateway network. Much like how a surgeon must perform procedures on a living patient while keeping all vital functions still taking place, the network of a space craft must be kept operational even during maintenance, upgrades, and reconfigurations. The tools provided by equipment manufacturers allow configuration tables to be developed and tested on the Earth, and for an orderly upgrade to proceed in a logical manner to ensure constant flow of data. As the Gateway progresses towards full operational capability, new modules will be added, and eventually visiting vehicles will be periodically attached [8].

Visiting Vehicles

Temporarily attaching a visiting vehicle to the Gateway provides an extra layer of complexity to the network. Any vehicles designed prior to the Gateway may be compatible with the QoS enhancements used but could implement them in slightly different ways. Furthermore, with multiple docking points possible for visiting vehicles, and the possibility of more than one vehicle at a time, the number of network configurations to be designed, built, and tested can easily grow exponentially. Thus, creating potentials for error introduction or hardware malfunction during reconfiguration. To minimize these risks, all visiting vehicles will have specific requirements to follow ensuring safety and reliability are not compromised [8].

Bent Pipe

While connected to the Gateway, the Orion Spacecraft will not join the Gateway TT Synchronization Domain and will only interact with the network using RC and BE traffic. Furthermore, while docked, the Orion will communicate with ground stations using a Bent Pipe method. Orion will transfer Space to Ground communications through the Gateways systems, allowing Orion Space to Ground systems to be powered down to lower power usage. This method will also be used with future spacecraft that may visit the Gateway [8].

4. TRADE OFFS

Speed vs Reliability

With any network architecture, there are multiple trade-offs to be considered, and the Gateway Inter-Element Network is no exception to this. In order to attain the desired reliability within the network, one major tradeoff is speed. Time-Triggered Ethernet (TTE) is a Quality of Service (QoS) enhancement to standard 802.3 Ethernet that enables the fault-tolerant transmission and reception of time- and order-critical Ethernet frames (temporal partitioning), which in turn enables the Ethernet network to support real-time and safety-critical applications. These QoS enhancements create a trade-off of lowered speed for increased reliability

The majority of traffic inside the network utilizes pre-defined Virtual Links for routing, with this specificity in place, the need for routers is mostly alleviated. TT and RC devices are connected to all three planes for two-fail fault tolerance, while BE devices are generally only connected to one plane. This creates an issue when an end system connected to one plane needs to communicate with an end system connected to another plane via BE. There are several methods to relieve this obstacle, however all come with an additional expense of various combinations of weight, cost, and network overhead. This concern is being investigated to determine the most appropriate solution, with all advantages and drawbacks considered.

Integrity vs Availability

The network architecture for Gateway includes switches having a Command/Monitor (COM/MON) function. By processing packets in separate channels within the switch then comparing the result the switch gains the capability to intercede and stop transmission of the faulty frame. This assures high integrity data with the possibility of lower availability. The incomplete frame would not pass the Cyclic Redundancy Check (CRC) performed by the next device in its path and would therefore be dropped as a fail benign event. By utilizing COM/MON functions, erroneous data produced by a faulty switch on the Gateway would be contained while awaiting switch recovery operations [5].

5. VERIFICATION

Testing and benchmarking performed in ANVIL

To facilitate initial testing and benchmarking, NASA is creating demonstrations and performance testing in the Artemis Network Validation and Integration Lab (ANVIL) at Johnson Space Center (JSC).

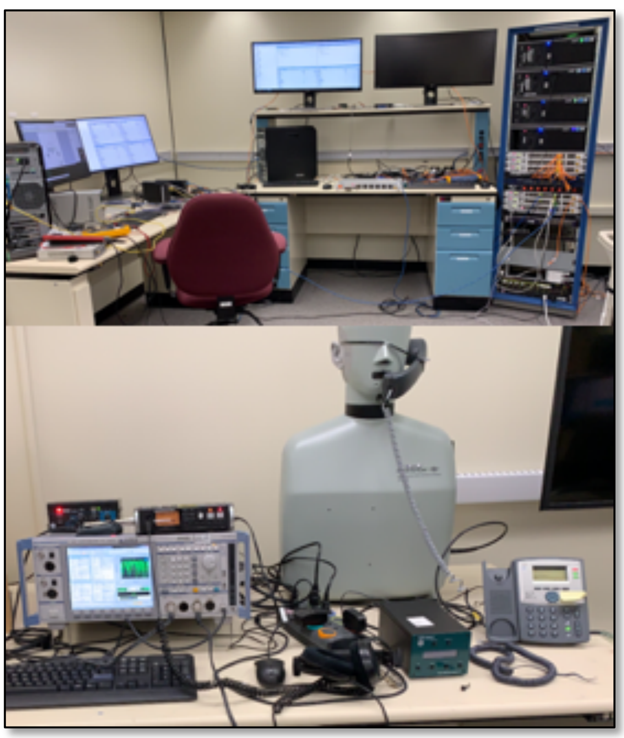

Figure 3. ANVIL Video Audio performance testing

The lab has already demonstrated audio and video data flow between PPE and HALO modules via 3-planes 3-edge switches.

ANVIL will consist of non-flight capable hardware that performs identically to space rated hardware with less initial investment. The ANVIL will be used to perform initial capabilities testing for Gateway equipment, and to provide benchmarks for future updates. Currently, the lab has equipment to emulate PPE and HALO, but has plans to integrate Orion, the Human Landing System (HLS), and Logistics Modules for network testing [9] shown in Figure 4.

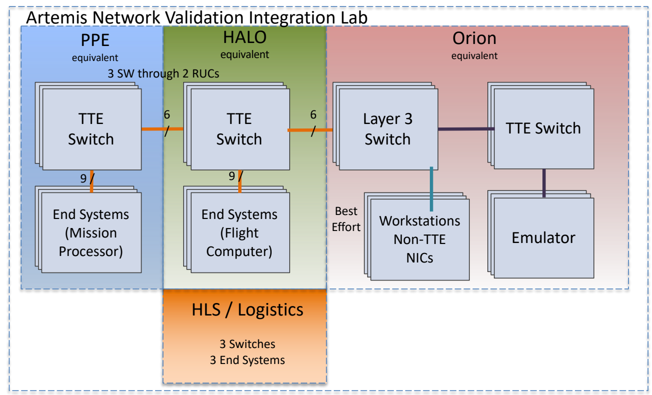

Figure 4. ANVIL layout

As Gateway progresses, the Gateway Reliability Avionics Integration Lab (GRAIL) will be constructed using flight rated hardware and will be as faithful as possible of a replica of Gateway. The purpose of GRAIL will be to perform verification tests on Gateway prior to launch, and as a realistic testbed to perform verification tests prior to usage in flight. The GRAIL will be to the Gateway Program what the Shuttle Avionics Integration Lab (SAIL) was to the Shuttle Orbiter Program. The major objectives for SAIL included "Systems level investigations and verifications for: Mission Unique Software, Mission Functional Requirements, Operational Anomalies, and Effects of System Design Changes." [20] The GRAIL will be used in a similar fashion to test avionics from the relative safety of a lab, before usage in space.

GRAIL build-up

GRAIL will be built in stages, beginning with what is termed Gateway in A Box (GIAB). GIAB is a low fidelity software emulation of the Gateway Spacecraft that can be used for flight control simulations. The next step is Gateway in A Rack (GIAR). GIAR is a medium fidelity hardware emulation of the Gateway that contains non-flight capable hardware that operates identically to flight hardware but does not contain a full complement of all components included on the Gateway. For example, GIAR contains embedded processor cards interfacing to switches shown in Figure 5. As the program completes each stage, the final goal is for GRAIL to be as faithful a reproduction of Gateway as possible.

Figure 5. Embedded Systems for GIAR

NASA is Vehicle Integrator, Vendors tests modules, NASA tests system.

The Gateway program is being designed and built by multiple contracts, rather than with a prime contractor as previous programs used. Each module will be completed using the requirements NASA has provided the company awarded the specific contract and will be validated and verified to perform as required. In addition to providing the space capable item to NASA, contractors will provide non-flight modules to NASA for integration into GRAIL. Upon receipt of the component test article, the module will be incorporated into the GRAIL facility for system level validation and verification. Once GRAIL is complete, any changes to flight hardware will be built and tested prior to launch.

6. Conclusions

As a result, the Gateway is building upon a topology from lessons learned behind the network centric approach of previous ISS architecture and network operations [10]. The approach provides a flexible and robust method to flow data while in a cislunar radiation order environment. The design also enables segmented testing scaling up to complete end-to-end testing. Future work includes details of spacecraft clock distribution, schedule generation, and reconfiguration.

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BIOGRAPHY

Paul Muri *serves as NASA Johnson Space Center's command and data handling system manager for Gateway Command and Data Handling and the deputy for the International Space Station. Paul received his BS, MS, and PhD in Electrical Engineering from University of Florida. While at the university Paul researched in the Wireless and Mobile Systems lab. As a NASA Space Technology Research Fellow, he demonstrated how Delay Tolerant Networking protocols increases video throughput in satellite networks. Previous to NASA JSC, Paul worked for Boeing Satellite Systems in Los Angeles, designing satellite payload and ground communication systems for critical reviews, new business proposals, and global ITU regulatory spectrum affairs. Paul has also interned at Motorola Solutions, Schlumberger, and NASA Goddard Space Flight Center.*

Svetlana Hanson *received her B.S. and M.S. in Computer Science and Systems Engineering from Moscow Institute of Transport Engineering (MIIT) in 1992 and M.S. in Applied Data Science from Syracuse University in 2020. She is involved in Flight Software and Avionics on Gateway, including TTE deterministic fault tolerant architecture. Mrs. Hanson is a recognized expert in digital transformation, big data, IOT, and emerging technologies.*

Martin Sonnier *serves as a Pathways Intern at NASA's Johnson Space Center. Martin retired from the United States Air Force after 21 years of service and is currently pursuing a BS in Computer Engineering at the University of Houston Clear Lake. During his time in the military, Martin worked as a telephone & switchboard technician, performing component level maintenance on various circuits, and also worked as a Management Analyst performing manning studies at the Air Force level. While at the university, Martin researched Mixed Criticality Systems and co-authored a paper that was presented at the University of British Columbia, Canada.*