Flight Avionics Hardware Roadmap

Avionics Steering Committee

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NASA/TM–2013-217986

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Avionics Steering Committee

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April 2013

Preface

All roadmaps represent a snapshot in time and are expected to evolve over time. This roadmap used the best available information from multiple sources to build a strategy for NASA's Avionics Steering Committee (ASC) which represents through its line management representatives the agency's avionics workforce chartered out of the Office of Chief Engineer (OCE). It is understood that Centers, Directorates, Divisions, Offices, and other organizations may be independently engaging in roadmapping efforts with overlap to this ASC effort. Whenever possible we have attempted to draw from these other efforts in building this roadmap. The ASC recognizes the value of roadmapping at many levels and views these activities as synergistic.

The approach taken by the roadmapping team was to focus on "the 80-percent solution," i.e., to identify technologies for NASA use that would meet on the order of 80-percent of defined NASA needs, specifically avoiding high-cost technologies with limited utility to the broader NASA mission set. The team also focused on developing a document that would inform, but not proscribe, future NASA technology development investments such as common avionics, high-performance space computing, or next generation spacecraft interconnect initiatives.

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Acknowledgements

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Introduction

As part of NASA's Avionics Steering Committee's stated goal "to advance the avionics discipline ahead of program and project needs," the committee initiated a multi-Center technology roadmapping activity to create a comprehensive avionics roadmap. The roadmap is intended to strategically guide avionics technology development to effectively meet future NASA missions' needs. The scope of the roadmap aligns with the twelve avionics elements defined in the ASC charter, but is subdivided into the following five areas:

- Foundational Technology (including devices and components)
- Command and Data Handling
- Spaceflight Instrumentation
- Communication and Tracking
- Human Interfaces

This effort addressed only flight avionics hardware and did not consider ground-based electronics, flight software, or ground software. The decision to focus on flight avionics was driven by the following considerations:

1. General purpose ground-based electronics such as are used to support general design, test, and simulation activities will utilize state-of-the-art commercial-off-the-shelf products and there is no reason for NASA to track or invest in it as a technology area.
2. Ground computing that will benefit from utilization of the same electronic/avionics equipment that is used for flight systems, e.g., hardware-in-the-loop testbeds, should be using the flight avionics chosen for the mission or mission set that they are supporting, and thus will be driven by the flight avionics that are the subject of this roadmap.

Foundational technology comprises low-level fabrication and materials technologies (such as Complementary Metal-Oxide Semiconductor [CMOS] processes), devices built on these technologies (such as transistors), and components built up from these devices (such as processors and memory chips). Command and Data Handling, Spaceflight Instrumentation, Communication and Tracking, and Human Interfaces are avionics subsystem-level technology areas that are enabled by and built from foundational technology components. Avionics systems are considered to be mature enough for project infusion at Technology Readiness Level (TRL) 6. Projects can then utilize these systems to build capabilities that enable or enhance NASA missions. See the example technology flow below.
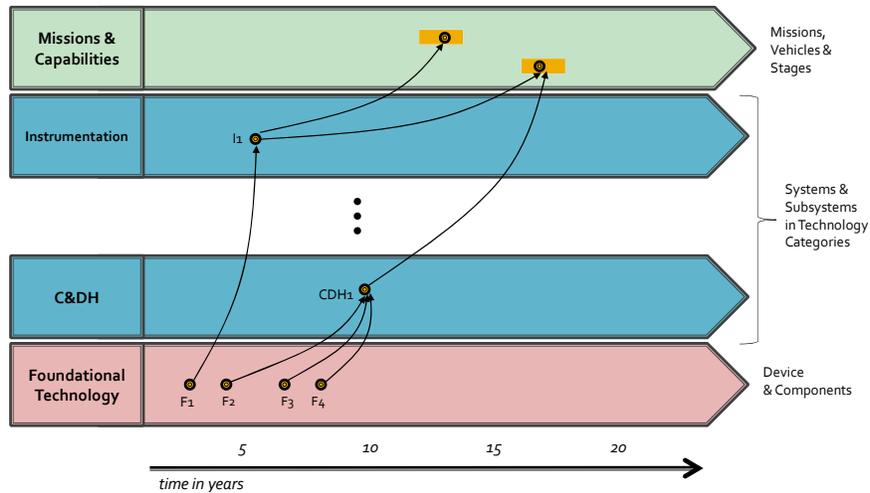
Figure 1. Example technology flow from foundational technologies through NASA missions

The subsystem categories (Command and Data Handling, Spaceflight Instrumentation, Communication and Tracking, and Human Interfaces) were those areas identified by the ASC charter as comprising "avionics." The roadmapping team analyzed each of the 14 Office of the Chief Technologist (OCT) Technology Roadmaps to identify technology needs in each of these areas to support future NASA projects and mapped them into these subcategories.

The roadmap looks out over a 20-year period. The near term tends to focus on evolving technologies while longer-term technologies tend to be more revolutionary than evolutionary. This long-term view allows for a balanced push-pull technology portfolio and development strategy with broad TRL diversity. A long-term technology view also requires that the roadmap be revisited periodically as new and unforeseen breakthroughs occur, NASA's missions change, and funding profiles affect technology timelines.

NASA Missions
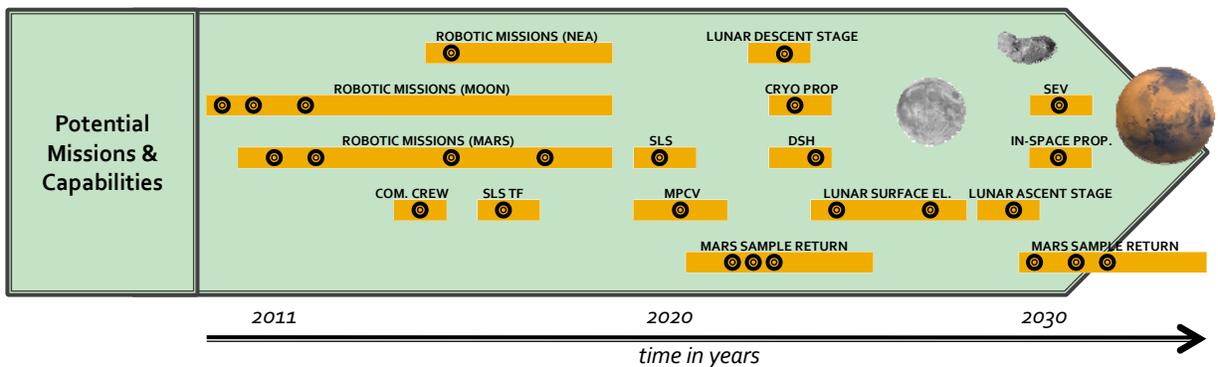
Figure 2. Potential future NASA missions and capabilities (vehicles, stages, habitats, etc).

A new class of future NASA missions is the primary driver of avionics technology. As NASA missions move farther from Earth and become increasingly more complex, new challenges arise. In support of new exploration and science destinations, NASA has adopted a flexible capabilities-based approach. This allows certain vehicles, habitats, satellites, and stages to be designed and built without a specific destination being selected. Current Design Reference Missions (DRMs) and roadmaps focus on Near Earth Asteroids (NEA), Earth's Moon, Mars, and primitive bodies within the solar system as well as operations in unique orbits such as the L1 and L2 Lagrange Points. From an avionics perspective these new capabilities and missions will present unique challenges. Key avionics drivers will be reliability and autonomy. Long-duration crewed missions as well as space-based observatories and solar system tours will require sophisticated reliability and fault tolerance. The current exploration DRMs call for 348 to 399 days of reliable operation, while robotic science missions specify many years of unattended operation. Furthermore, the communication delays and challenging orbital dynamics of NEA and extreme science missions require increased autonomy and on-board decision infrastructure. Traditional solutions to reliability and autonomy increase processing demands and redundancy which in turn drives system mass and power. Advanced technologies and approaches are needed to support these challenging missions.

NASA's short-term strategy is to continue robotic exploration of the Moon, Mars, and NEAs. The Lunar Atmosphere and Dust Environment Explorer is scheduled for launch in 2013, Mars Science Laboratory launched this year, Mars Atmosphere and Volatile Evolution mission is targeting a 2013 launch, the Exobiology on Mars mission has a 2016 launch, and the Origins-Spectral Interpretation-Resource Identification-Security-Regolith Explorer, mission is planning to launch an asteroid sample and return mission in 2016.

While robotic exploration continues, NASA will develop capabilities in support of human exploration to destinations such as the Moon, a NEA, and eventually Mars. The NASA Human Architecture Team has identified nine transportation elements: Solar Electrics Propulsion, Chemical Propulsion Stage, Deep Space Habitat, Space Exploration Vehicle, Lunar Orbit Rendezvous Lander, Cargo Carrier, Space Launch System (SLS), Multi-Purpose Crew Vehicle (MPCV), and Nuclear Thermal Propulsion. The first two elements, SLS and MPCV, are planned for 2020, with test flights as early as 2017. Other elements depicted in later years on the roadmap build capability for more sophisticated and challenging missions. Extremely challenging robotic missions (i.e., Mars Sample Return) are also being considered.

These missions, characterized by long duration, vast distances, harsh environments, and in some cases the human element, require new avionics technologies to be developed to meet mission requirements for exploration and safely bring crews back to Earth.

In the following sections, we identify the key technologies needed to support these missions and the time frames in which they are needed, or are expected to be available.

Many of these technologies are anticipated to be developed by industry or other agencies e.g., Department of Defense, Department of Energy, and need only be monitored to track their progress and determine when they can be adopted for insertion into NASA missions. A minority of the technologies discussed below will require NASA investment to mature in a way that will be of use to NASA.

Foundational Technology
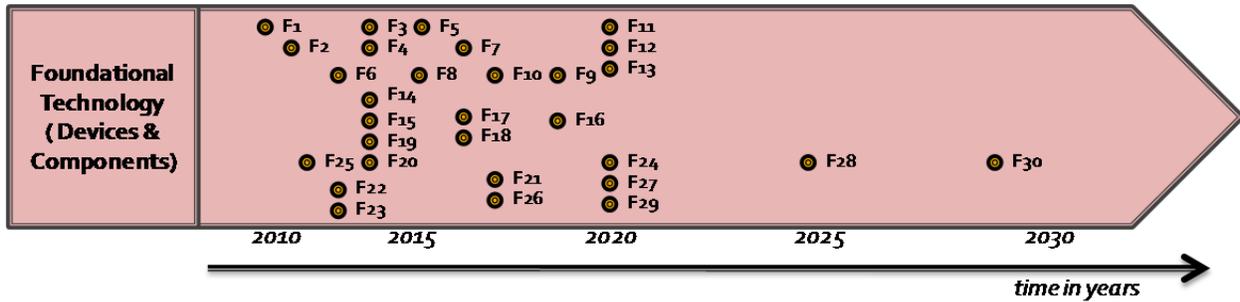
Figure 3. Foundational Technology timeline.

Processor Technology and Radiation-Hardening by Design (RHBD) Library

F1: 45-Nanometer (nm) commercial multi-core processor

F2: 32-nm commercial multi-core processor

F3: RHBD bulk CMOS Library for digital Application-Specific Integrated Circuits (ASICs) by QML IBM 90-nm CMOS line

F4: RHBD Silicon-On-Insulator (SOI) Library digital ASICs by QML IBM 45-nm SOI line

F5: 90-nm bulk CMOS or 45-nm SOI RHBD multi-core processor

A Boeing-developed RHBD 90-nm bulk CMOS standard cell library was originally funded by the Defense Threat Reduction Agency (DTRA) and the Defense Advanced Research Projects Agency (DARPA) and is currently in the process of being commercialized by several companies. The library provides the capability to relatively inexpensively develop radiation-hardened digital ASICs. A QML-certified line is expected to be implemented at IBM with expected QML certification in 2014. It is expected that DTRA will initiate a follow on 45-nm RBHD program with the IBM SOI CMOS process with a target completion date of 2014. Similar efforts are ongoing at other companies. NASA does not need to invest in this semiconductor technology, though additional funding could be used to accelerate the development schedule and to influence the types of cells to be developed, the testing to be performed, and the selection and fidelity of the development vehicles to be designed/validated. However, NASA can use this standard cell library and associated tools to develop ASICs and standard products at greatly reduced costs, compared to current approaches.

Digital ASICs, with possible extension in some environments to mixed-signal ASICs, based on SOI RHBD have the potential to operate beyond the military standard temperature range of -55°C to 125°C, as well as providing radiation hardness. CMOS and SOI are demonstrated to generally work well at low temperatures with faster speed and lower leakage current, but work is required to determine operational characteristics over the

wider temperature range and to develop design rules, tools, and possibly circuit library modifications to enable wider temperature operation. This will require NASA investment as only NASA will utilize these capabilities, but it leverages the DTRA/DARPA sponsored RHBD standard cell library and associated tool set.

A general purpose multi-core processor and a Single Instruction Multiple Data (SIMD) multicore processor utilizing 90-nm RHBD have been developed or are in development, and could be ready for mission insertion within a relatively short time. These processors are derived from commercial processors and similar to the commercial two- to four-core machines currently in use. The Maestro processor contains 49 general purpose processor cores, four high speed Double Data Rate (DDR) 2 memory ports, four 10 Gigabits Per Second (Gb/s) XAUI Input/Output (I/O) ports as well as Gigabit Ethernet and GPIO ports and is similar to a cluster computer architecture on a single chip. While this processor has been incorporated into several board-level products for evaluation and software development, it is not applicable, in general, to NASA missions due to a lack of power management and fault tolerance capabilities. A second-generation machine in either 90-nm RHBD, or in 45-nm SOI CMOS RHBD, based on the Maestro architecture and compatible with the Maestro software suite, would support a broad range of NASA missions and be relatively easily inserted into future missions. Depending on technology selection and levels of power management and fault tolerance included, it could be available at TRL6 in the 2013-15 time frame. Such a machine would be greatly enhancing, if not be enabling, for Mars Sample Return, Asteroid/Comet Sample Return, NEA, and human and human-robotic precursor missions.

Radiation-Hardened (RH) Extreme Temperature Technology

F6: 0.5-Micrometer (μm) Silicon-Germanium (SiGe) RHanalog ASICs

F7: 130-nm/180-nm SiGe RH analog ASICs

F8: 0.5-μm SiGe RH wide temperature analog interface and analog/digital conversion component

F9: 130-nm SiGe RH wide temperature analog interface and analog/digital conversion component

F10: RH wide temperature SiGe switching point of load converter in 0.5-μm

F11: RH wide temperature SiGe switching point of load converter in 130-nm

F12: Silicon carbide (SiC) mixed signal electronics for high temperature application

F13: Gallium nitride (GaN) radio frequency electronics for high temperature applications

F14: Structured RH wide temperature ASICs

SOI and SiGe have been demonstrated as the digital and analog technologies of choice for radiation-hardened extreme environment electronic application in a wide temperature

range beyond the military standard of -55°C to 125°C. SOI and SiGe for extreme temperature radiation-hardened analog ASICs exhibiting radiation hardness to 300 kilorads (krad) and capable of operation over a temperature range of at least -140°C to 125°C have been demonstrated. Analog ASICs in 0.35-µm SOI and 0.5-µm SiGe have either been developed or are being developed for motor control systems capable of operating for long lifetimes in the Mars environment (-135°C to 85°C). Currently, the 0.5-µm SiGe technology needs additional investment to complete circuit library and tools development. A next-generation SOI and SiGe extreme temperature RH technology would provide additional capability, reduced power, and long-term availability of the technology. Recommended target date for completion of a 0.5-µm SiGe circuit library and calibrated tool set is 2013 to support future missions, including Mars 2018 and projected primitive body science missions. A recommended target date for completion of 180/130-nm technology is 2016 to support a broad range of future missions including ExtraVehicular Activity (EVA), primitive bodies, and future Mars missions.

SiC and GaN have been demonstrated as potential technologies for RH high temperature applications beyond 300°C. There have been many process and reliability improvements as well as design enhancements in these technologies during the past years that position them as the most promising candidates for high temperature applications for NASA missions, especially an in situ mission to Venus.

RH structured ASICs are becoming available today. These components can survive extreme environments, provide quick turn around, and be procured at relatively low cost for digital and mixed-signal ASICs (they may not be as radiation hardened or as extreme temperature capable as SOI or SiGe RHBD ASICs, but they are significantly lower cost, faster turnaround, and suitable for a broad range of missions). Need date is 2014 to support all future missions. With additional investment by NASA, development of additional configurations of structured ASICs, as well as additional extreme temperature characterization of these devices can be provided by the companies currently developing these components.

Electronic Packaging Technology

F15: Advanced electronic packaging qualification

F16: Through Silicon Via (TSV) chip stack technology for space qualification and applications

There are several advanced packaging technologies that would improve mass, volume, and power of spacecraft avionics. Candidate technologies include: stacked chips/packages/modules, high density interconnect, and chip-on-board technologies. Guidelines and design rules for use in space environments, as well as qualification requirements and procedures, need to be developed for a minimal but optimum subset of available commercial packaging technologies. Once this is done, qualification of this optimal subset can proceed. This is not a traditional technology investment, but an

adaptation and qualification of existing commercial/military technologies, and should be coordinated with programs such as the NASA Electronic Parts and Packaging Program. Recommended target date is 2014 to support Mars 2018, Europa, and future science and exploration missions, all of which will benefit from the volume and mass reduction of these advanced packaging technologies.

TSV chip stacks allow direct stacking of silicon chips with metalized vias placed anywhere throughout the chip. This basic technology, developed by the Massachusetts Institute of Technology (MIT) Lincoln Laboratory, is currently available from several commercial vendors. It provides the ability to develop a series of stackable integrated circuits that can be mixed and matched as necessary to provide required capability. The advantage here is that due to extremely short distances and low capacitance of interconnect, the stack essentially operates as a single chip with all the power and speed advantages inherent in monolithic systems. Additionally, due to elimination of single chip packaging and interconnect, volume and mass are reduced and reliability increased. The technology is being developed for commercial use, but NASA use requires extension of the technology to extreme temperatures and across multiple semiconductor processes, e.g., SOI CMOS and SiGe. Recommended target date is 2018 to support future missions including EVA and small/micro-satellites for all exploration and science missions.

RHBD Network Technology

F17: 90-nm CMOS RHBD network interface and switch components

F18: 45-nm SOI RHBD network interface and switch components

F19: RH fiber optic transceivers for >3-Gb/s data process and transmit

Future NASA space missions will require extremely high bandwidth spacecraft interconnect systems. The venerable 1 Megabit Per Second (Mb/s) 1553 is being superseded by 250-Mb/s SpaceWire and, in the Human Exploration and Operations Mission Directorate (HEOMD), by the upcoming 1-Gb/s Time-Triggered Gigabit Ethernet (TTGbE) standard. Next generation missions, however, with multi-gigabit instruments, onboard science, and autonomy processing, will require multi-gigabit interconnect bandwidth as well as real-time determinism, fault tolerance, power/bandwidth scalability, and seamless interoperability between copper, fiber optic, and wireless physical (phy) media layers. Host data transmission modes including broadcast/multicast/point-to-point, and synchronous/asynchronous will also be required. Several standards for space systems are likely to emerge, including time-triggered 10-gigabit ethernet, a space version of Serial Rapid I/O, and Space Fiber. The Next Generation Spacecraft Interconnect System committee is developing one such standard with participation from NASA, the Air Force Research Laboratory, Space and Missile Command, the National Reconnaissance Office (NRO), the Naval Research Laboratory, the American Institute of Aeronautics and Astronautics, VITA, Lockheed Martin Airospace Corp., Boeing Corp., British Aviation

Electronics, Honeywell Corp., and others. Network interfaces, routers, switches, and endpoints supporting these protocols, as well as Serializer/Dererializers and phy-layer transceivers will be forthcoming from space avionics and component vendors, most likely implemented in 90-nm and below RHBD technologies. There is a concern that, as in the past, offerings from multiple vendors will not be interoperable. The NGSIS is attempting to ensure interoperability by virtue of a tight specification and validation criteria that guarantee interoperability, but NASA will need to invest resources to ensure that these standards meet unique NASA requirements as well as to ensure both interoperability and ease of use of component offerings.

Copper interconnect at these speeds is relatively well understood, but difficult to achieve in radiation hardened and extreme temperature capable versions with the desired isolation, fault tolerance, and power management features that are available in fiber optic. Fiber optic implementations, however, do not provide extreme radiation and temperature tolerance, while copper wire implementations are not well suited to longer transmission distances and do not offer good isolation at high frequency.

Radiation hardened fiber optic phy-layer technology is progressing to the point where it is a viable alternative to copper in many spacecraft systems. Radiation tolerance of 100 krad has been achieved with data rates of >3 Gb/S over hundreds of meters in extremely small packages with easy assembly, and good tolerance of temperature, vibration, and shock. In addition to reducing power and providing electromagnetic interference-free operation and electrical isolation, this phy-layer medium can provide transparent and seamless chip-to-chip, board-to-board, and box-to-box interconnect. NASA investment is required to meet NASA's unique requirements (radiation, shock, vibration, temperature, long life, high reliability). The recommended target date is 2014 to support future high data rate science instruments and exploration missions.

Wireless interconnect phy-layer is not being addressed. Wireless interconnect offers a host of advantages in NASA missions, eliminating the mass, power, and unreliability of cables and connectors, providing ease of integration and test, and allowing simpler reconfiguration, sparing, fault tolerance, and retrofitting of systems. NASA support will be required to develop a wireless standard compatible with the advanced protocol(s) currently under development and interoperable with wire and fiber optic based systems.

RH Memory Technology

F20: High density RH memory components in Static RAM (SRAM) and Dynamic RAM technologies

F21: 20-nm Silicon-Oxide-Nitride-Oxide Silicon (SONOS) and Phase-Change RAM (PCRAM) flash memory

F22: 130-nm Ferroelectric RAM (FeRAM) flash memory

F23: 65-nm Magnetoresistive RAM (MRAM) flash memory

F24: Resistive memory

Currently, radiation hardened CMOS SRAM, SONOS and PCRAM are available as volatile and non-volatile memory options up to 16-Mb per die. One-time-programmable Programmable Read-Only Memories and Metal-Nitride-Oxide-Silicon electrically Erasable PROMs have been used in space applications since the 1990s. Today, RH high-density memories utilizing more advanced memory technologies are needed for space systems to provide improved power utilization at orders of magnitude increase in density (which translates to mass, volume, and complexity reduction). While RHBD can be applied to achieve RH non-volatile memory cells at the cost of additional power and density, other non-volatile memory technologies, such as PCRAM, MRAM, FeRAM and Resistive RAM, provide improved density and power utilization with improved radiation tolerance. These memory cell technologies will, however, still require RH CMOS control logic, which can be provided by RHBD technologies with minimal impact to overall component power or density. These alternative memory cell technologies are at relatively low TRL levels and will require investment to mature them into reliable, manufacturable technologies and to then use these memory technologies to develop memory components and embeddable macros suitable for use in NASA missions.

RH Reconfigurable Field-Programmable Gate Arrays (FPGAs) for Computing Technology

F25: RH FPGAs for reconfigurable computing

F26: RH reconfigurable compute-element chips for reconfigurable computing

Radiation-hardened and extreme temperature-capable FGPAs for use in avionics systems, both as single function implementation vehicles and as core elements in reconfigurable computing are required to meet the processing throughput, flexibility, fault tolerance, and power-to-performance levels desired for future NASA spacecraft. These components can be developed by utilizing RHBD libraries and processes from several sources.

Radiation-hardened devices, fault-tolerant architectures, reusable cores, development tools and practices, and validation and integration standards are needed for reconfigurable computing for space system applications. These deficiencies translate to technology gaps in the reconfigurable computing development path from the FPGA-based reconfigurable machines of today to more general morphware-based machines of tomorrow. In overcoming these gaps, technology developments in fault tolerance, system-on-chip architectures, design-time tools and reconfigurable hardware run-time systems, and re-usability via integration standards and system modularity are required.

In addition to standard FPGA architectures, higher level reconfigurable architectures are highly desirable as they provide the ability to work at higher levels of integration at reduced power for a given level of performance. Instead of working at the virtual gate or look-up table level, these devices work at the compute-element level, allowing higher

power efficiency and simplified design. As with FPGAs, they need to be implemented in 90-nm and below RHBD technologies.

Nano-electronic Technology

F27: Carbon nanowire-based transistors and electronics

F28: Carbon nanotube-based transistors and electronics

F29: Graphene-based Terahertz (THz) transistor technology

F30: Graphene-based high-speed circuits and electronics

Nano-technology including carbon nanowire, carbon nanotube, and graphene-based technologies are promising candidates to sustain the relentless progress in scaling for CMOS devices. With nanowire and nanotube field-effect transistors and devices as well as graphene-based 300GHz transistors having been demonstrated, the nanotechnology roadmap projects THz transistor technology by 2020, and graphene-based high-speed circuits and electronics by 2028. Nanowire, nanotube and/or graphene-based ASICS are projected to replace silicon-based electronics in future electronic systems and can be applied in most applications, such as digital, photonics, analog, and mixed-signal.

Fundamentally, these nano-technologies offer higher levels of integration and lower power through smaller transistors and higher electron mobility than is achievable in silicon-based technologies. They also offer inherent radiation hardness and robustness to environmental stresses. Graphene is a mono-layer of carbon in a "chickenwire" configuration. It offers high electron mobility and radiation hardness at extremely small feature size and thus low power. Transistor equivalent structures have been built using stacked (mono) layers of graphene and separating dielectrics, but deposition and patterning methods suitable for large-scale manufacturing have not yet been developed. Carbone nanotube and nanowire technologies promise extremely high conductivity wiring both on-chip and off, but suitable manufacturing technologies have not yet been developed. Investment by NASA will be required to tailor these technologies and devices to NASA's unique requirements, but as these technologies are not yet at TRL3, it is not clear what investments will be required to meet NASA needs.

# Command and Data Handling (C&DH) Technology
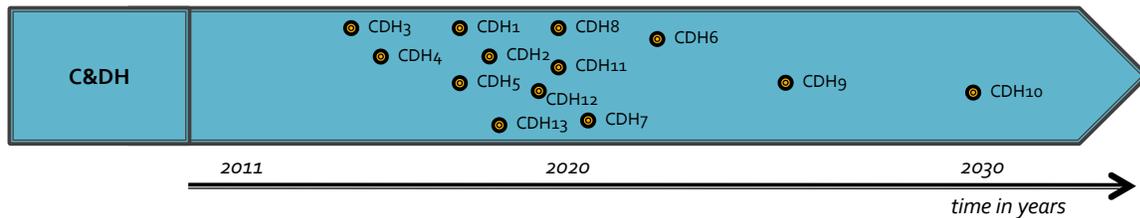
Figure 4. Command and Data Handling Technology timeline.

C&DH refers to the board- and subsystem-level integrated components using devices and foundational technologies. NASA's future endeavors will often require integrated devices and systems which are RHBD and capable of performing with the lowest mass and power profiles that can be achieved. However, it is also expected that some commercial non-radiation hardened, higher performance capabilities should also be leveraged to meet performance, fault tolerance and recovery, power management, or other unique requirements. It is expected that these systems will have some inherent radiation tolerance but not to the level of RHBD devices and systems.

Processing

CDH1: Single Board Computer (SBC) – 90-nm RHBD multicore processor

CDH2: SBC – 45-nm RHBD multicore processor

High performance multicore computing in the commercial sector provides orders of magnitude increase in processing throughput as compared to independent chips with several processors on a board. NASA should leverage the work that the NRO has invested through Boeing to develop a RHBD multicore processor called Maestro 49, based upon the Tilera Tile64 processor, itself an outgrowth of the Raw processor developed by MIT for DARPAs Polymorphic Computing Program. In addition to the processor itself, NRO developed a complete software suite as well as software development tools and system. Final test and debug of the Maestro system as well as radiation testing is currently under way. However, specific shortfalls of the Maestro design include: insufficient fault tolerance, non-deterministic programming model, high power consumption and thermal load, poor power and energy management and scalability, and severely suboptimal I/O and memory interfaces. NASA can leverage all of this previous work by developing a next generation Maestro-type machine by adding fault tolerance, power management, and other requisite features.

CDH3: SBC – 45-nm non-RHBD multicore processor

CDH4: SBC – 32-nm non-RHBD multicore processor

Non-RHDB CMOS and SOI technology advances (90-nm down to 32-nm) should be leveraged to the greatest extent possible to provide low-cost, high-performance options for

non-critical, specialized applications. Both general-purpose processing as well as specialized computing architecture trends should be leveraged.

CDH5: Low power, extreme environment 45-nm System On Chip (SOC)

With the advent of 90-nm, 45-nm, and eventually 32-nm commercial and RHBD ASICS, as well as radiation-hardened, structured ASICS now becoming available, it is feasible to develop extremely low mass/volume/power, highly capable avionics as a SOC for small spacecraft. Such a device would, ideally, be built from a set of standardized modular, plug and play IP modules that could be relatively easily ported and validated in a modular, piece-wise fashion to next generation semiconductor processes.

CDH7: RHDB reconfigurable computer architecture

Reconfigurable (or hybrid) computing architectures take advantage of the flexibility of software in combination with the high performance of hardware by processing with very flexible high-speed computing fabrics like FPGAs. This enables the loading of a new circuit on the reconfigurable fabric of the FPGA during runtime. It is expected that NASA's missions will require ever-increasing autonomy to make real-time and non-real-time decisions. In addition, the flexibility afforded by reconfigurable systems will result in lower mass-to-orbit to perform a wider range of functions for any particular mission.

CDH10: Three-Dimensional (3-D), highly-integrated computer system

Three-dimensional integration uses multiple vertical layers of transistors to improve performance instead of the single layer of transistors that most modern integrated circuits use today. 3-D integrated circuits can be built using wafer-on-wafer, die-on-wafer, or die-on-die methodologies to potentially offer vast improvements in cost, bandwidth, power, and volume using TSV technology. TSV allows semiconductor die and wafers to interconnect to each other at higher levels of density. A 3-D, highly-integrated computer system with processing, interface, and memory resources based upon TSV technology might be possible in the 2025 – 2030 timeframe.

CDH11: Ultra-low power radiation-hardened, graphene-based computer

Graphene is basically a layer of carbon that is only one atom thick with extremely strong physical properties and highly conductive of electricity. Electrons can fly across graphene at blazing speeds. The future potential of this material is immense and it is expected that graphene will eventually change the entire landscape of computing infrastructure as a replacement for silicon. A radiation-hardened, low-power computer based upon this technology would be enabling for future NASA missions.

CDH13: Digital signal processing

In addition to multicore Multiple Instruction stream Multiple Data stream (MIMD) processors, NASA can leverage other technologies being developed for the signal processing community. These include SIMD and Very Long Instruction Word architectures

with high memory bandwidth and multiple processing units for image processing and other highly parallelizable applications.

Network Devices and Interconnect Hardware

CDH8: 90-nm and 45-nm RHBD card-level network interface controllers and network switches

CDH9: High performance (10-Gb/s+), low power, scalable interconnect

CDH11: Gigabit-rate network router

Network interface controller, switch, and router technology maturation is needed. Network switch technologies are needed to support fault tolerant networking in building highly reliable systems and to meet data transfer demands for future missions. Coupling time-triggered switch technologies and other commercial network technologies with radiation-hardened/radiation-tolerant processes will produce next generation high-speed low-power networking architectures, including components such as gigabit network routers.

RHBD Memory Cards/Subsystems

CDH6: Volatile mass memory cards/subsytems

CHD12: Non-volatile mass memory cards/subsystems

Commercial memory cards have poor radiation characteristics, while traditional radiation hardened memory devices are low density and relatively slow. Radiation-hardened, high-density, high-speed memory devices (volatile and non-volatile) are needed in combination with advanced processors and instruments to survive the expected environments that NASA will encounter and to provide the required performance. Radiation hardened, multi-gigabit DDR2 and DDR3 SDRAMs are feasible and necessary to build these systems. In addition to cards and modules, file-based recorders are needed for data storage and retrieval in data-centric architectures required for autonomous systems.

Spaceflight Instrumentation
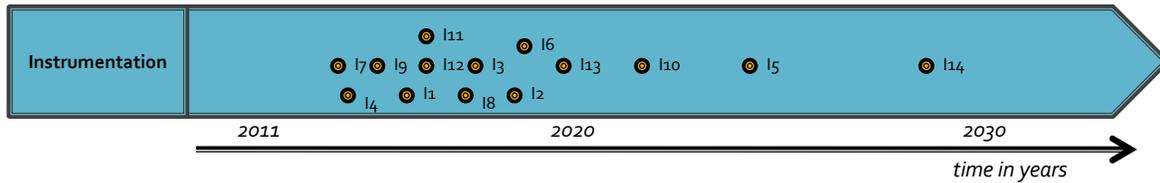
Figure 5. Spaceflight Instrumentation Technology timeline.

Spaceflight instrumentation refers to the sensors and systems used to measure environments or behaviors of spaceflight systems, subsystems, or components. A sensor is generally a single device used for making measurements, or a highly miniature set of components able to make 'smart' measurements. A 'smart' measurement results from the basic sensor reading being manipulated (e.g., adjusting the reading based upon a calibration curve or taking multiple measurements and synthesizing them into a single data point).

An instrumentation system is composed of multiple distributed elements, modules, or components that function together to process sensor measurements.

Sensors

I1: Miniaturized space-qualified pressure sensors for wide temperature range measurements

SOI MicroElectroMechanical Systems(MEMS) pressure sensors are highly radiation tolerant and can measure real-time pressure at high temperatures and in harsh environments. Transducers can be packaged for a wide range of temperature (-250F to +350F).

I2: Diamond MEMS pressure sensor

Current approaches to hydrazine measurements require isolation of the pressure sensor from the hydrazine environment, reducing accuracy of the measurement and producing a potential failure point. These failure points are realized regularly on longer duration missions and often require additional sensors be flown as a back-up. The proposed sensor eliminates these systems providing simpler measurement approaches, improved measurement accuracy leading to reduced margin requirements, and eliminates the need for redundant sensors on longer duration missions.

I3: Optical fluid sensing for high vibration and shock environments

Designs using optical sensors based upon laser excitation and interferometric techniques to determine fluid depth in flow, or fluid amount when dominated by surface tension and viscosity forces, rather than gravity, should be developed. Applications include cryogenic storage tanks and the flow of reactive cooling fluids.

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I4: Multi-channel cryogenic pressure sensor for high vibration and shock environments

Designs using miniature piezo-resistive silicon pressure sensors to measure cryogenic fluid pressure accurately to within 0.25-percent full scale should be developed. Applications include rocket engines, cryogenic wind-tunnels, industrial cooling, and cryogenic gas production.

I5: Molecular detection/trace gas detection sensors

Development of intelligent, autonomous, distributed sensors (wired and wireless) for highly sensitive gas detection is desired. The sensors are based on nanostructures that can potentially respond to a single molecule.

I6: Development of cryogenic video cameras

Developments in sensing of cryopropellants in microgravity and under impulse are needed for in-space propulsion systems for characterization of liquid level, slosh, and flow. Currently, video imaging is done through conventional cameras looking through windows which can present fracture problems. Alternative approaches to immerse the imager into the fluids present problems of both thermal control and assurance that the imager hardware does not contaminate the fluids.

Sensor/Instrumentation Systems

I7: Radio Frequency (RF) Identification (RFID)/Surface Acoustic Wave (SAW) wireless instrumentation system

Technology based on SAW development at the device level and with the interrogator RF system should be developed. A SAW-based instrumentation system helps to reduce instrumentation design complexity and avionics mass while reducing power requirements through passive sensing.

I8: Spacecraft Integrated System Health Management (ISHM)/Integrated Vehicle Health Management (IVHM)

Development of reliable, believable (i.e., no false-positives) sensing devices to enable the ISHM/IVHM type of implementations is needed. ISHM systems include: sensors, anomaly detection, diagnosis, prognostics, user interfaces to provide integrated awareness of system condition, and new systems engineering processes enabled by intelligent elements that are part of the ISHM knowledge architecture.

I9: Distributed/reconfigurable sensor modules in spacecraft

Developments in reconfigurable distributed avionics architecture can be based upon a small number of multi-purpose modules that can be individually changed to drive and sense a variety of mechanical and electrical components, characterized generally as either a multi-purpose electronic drive module or a multi-functional signal-conditioning module. The generic drive module can be configured to drive and control a variety of spacecraft

avionics components: valves, motors, solenoids, pin pullers, thermostats, and heaters. A generic sensor module will be able to sense and record data from a variety of spacecraft avionics sensors: thermocouples, resistive temperature devices, potentiometers, encoders, tachometers, accelerometers, gyroscopes, and level and pressure sensors.

I10: Smallsat attitude determination/control instruments

Development of inexpensive attitude determination/control instruments for small satellites (e.g., nanosat or cubesat) is desired. These instruments must be designed to use low power and small volume and provide high precision to increase pointing accuracy.

I11: Autonomous landing instrumentation

Development of precision landing and hazard avoidance instrumentation for autonomous landings is needed including instruments and associated processing systems for high-precision vehicle velocity vector determination, and altitude and attitude determination. Examples include Doppler lidar velocimeters, flash lidar, and radar mapping systems.

I12: Docking and close proximity operations instrumentation

Instruments and associated processing systems that enable safe real-time navigation and maneuvering in close proximity to small bodies, e.g., comets and asteroids as well as small moons and other primitive, low mass (low gravity) objects are desired. Used for autonomous robotic, teleoperated robotic, and crewed missions, these instruments are enabling for future solar system exploration and science missions. Examples include Doppler lidar velocimeters, flash lidar, and radar mapping systems.

I13: Portable photo-acoustic system for planetary exploration

Photo-acoustic systems are designed to detect specific molecular species with high sensitivity (up to parts per trillion), using an array of microphones and array of infrared/ultraviolet light-emitting diodes to determine exact location and quantity of gaseous species of interest.

I14: Autonomous lab on a chip

Development of miniature autonomous instrument sensors using 'smart' materials (i.e., materials with properties that can change in a controlled fashion by external stimuli) is desired. These instrument sensors have built-in capabilities to support sampling, sensor cleaning, and waste rejection schemes.

Communications and Tracking
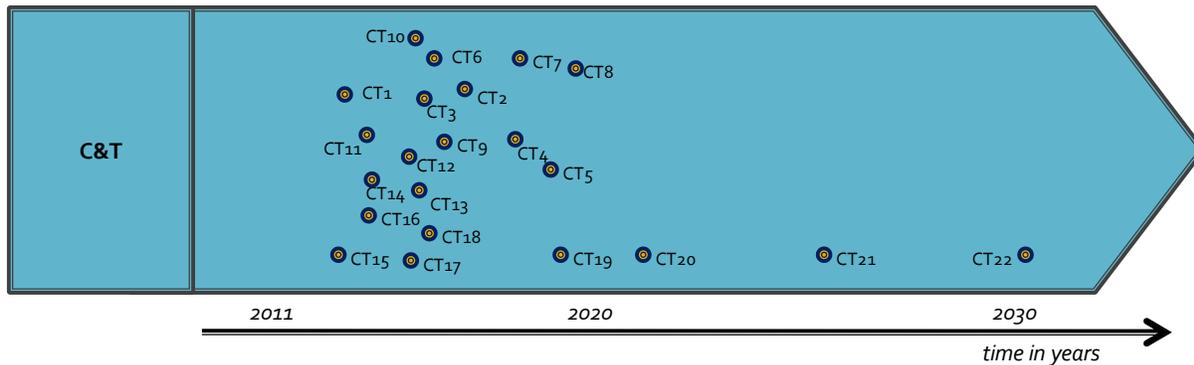
Figure 6. Communications and Tracking Technology timeline.

Networking Communications (Internetworking Communications)

CT1: Delay Tolerant Networking (DTN) technology maturation and validation using multi-center, International Partner and potentially International Space Station (ISS).

CT2: Communications Security (COMSEC)/mission assurance technologies for networked space communications

CT3: Mesh networking protocols – ad-hoc protocols (includes EVA applications for in-space and surface communications)

CT4: Surface wireless networks

CT5: Navigation/location aware networking

Current space communication scenarios, for the most part, have involved fundamental point-to-point links between a spacecraft and Earth. Today's specialized link-layer protocols and carefully planned and scheduled link operations have thus far been adequate to meet the needs of missions. However, with a more networked communications architecture that is envisioned for deep space exploration and planetary surface operations, existing protocols and methodologies will need to evolve. Internetworking protocols that handle long link propagation delays and outages, and support surface wireless and proximity, quality of service, network management and information assurance, ad-hoc networking, etc., are critical in providing reliable, end-to-end communications. The above foundational technologies provide the necessary framework for networked communications for deep space exploration.

Optical Communications for Deep Space

CT6: OCT optical communications demonstration

CT7: Deep Space (DS) optical terminal

CT8: DS optical ground stations

NASA is currently migrating to Ka-band for high-rate communications. However, it is anticipated that the demand for higher data rates will exceed the capacity available in the Ka-band spectrum given the mass and power constraints. At this stage, optical communications provide access to unregulated spectrum and will support the data rates needed by the next generation instruments, sensors, etc. Main challenges for deep space are the atmospheric issues and accurate acquisition and tracking of the target. These advances will be made with OCT TDM and other developmental test objectives.

Miniature reconfigurable communications for Beyond Earth Orbit EVA applications

CT1: DTN

CT3: Mesh networking protocols – ad-hoc protocols (includes EVA applications for in-space and surface communications)

CT5: Surface wireless networks

CT9: Methods for proximity tracking or localization in a Global Positioning System (GPS)-deprived environment

Methods for proximity tracking or localization are required for both robotic and human surface- and space-based operations. In some cases, proximity tracking is required to supplement global tracking by providing greater accuracy relative to local landmarks. In other cases, proximity tracking is required during outages or gaps in a global tracking service. Examples include a robotic element or rover finding its way back to a base or intra-habitat navigation by a free-flyer within ISS or a deep space habitat.

Space-Based Radios Using Ultra Wide Band or Other Formats

CT1: DTN

CT2: COMSEC

CT3: Mesh networking protocols – ad-hoc protocols (includes EVA applications for in-space and surface communications)

CT4: Surface wireless networks

CT9: Methods for proximity tracking or localization in a GPS-deprived environment

A next generation, miniature, reconfigurable radio is called for to support the mass, volume, and power constraints of deep space exploration suits (2018-2020). It should incorporate DTN, mesh networking, surface wireless networks, navigation/location aware networking, wearable antenna, etc., to provide a system capable of supporting in-space EVA as well as surface EVA/robotic missions.

Low Power, High Rate RF to Support High-rate Communications from NEN and Deep Space Network (DSN) (Bridge Gap to Optical)

CT10: Low power/mass transceivers for higher carrier frequencies such as X-band, Ka-band

To bridge the gap to optical communications from deep space as well as to provide high-rate communications between exploration vehicles (space–to-space or space-to-surface), a low-power, high-rate Ka-band system with higher order modulation, coding, etc. reducing the mass and power required is needed.   Mass and power reductions come with coding, miniaturization, advanced semiconductor technology, etc.

Low Voltage/Low Power Transceiver Module Energy Harvesting Technology

CT11: Development of space-qualified low power V-band transceivers for vehicle/satellite internal environments

CT12: RF energy harvesting technologies to drive V-band transceivers

CT14: Chip antennas for integration with transmitter or transceiver electronics

V-band could be beneficial for space-to-space (vacuum environment) at very high data rate links. Either vehicle to vehicle, or long haul. Hardware technology would include space qualified antennas, transceivers, and power amplifiers. V-band could also be used internal to the space vehicle for sensor data transfer/high data rate devices such as High Definition (HD) video, displays, laptops, and biomedical hardware.

Sensors with integrated transmitters such as a thermocouple with transmitter all run off of parasitic energy sources. V-band could be used internal to the space vehicle for sensor data transfer/high data rate devices such as HD video, displays, laptops and biomedical hardware.

Spectrum analysis tool for Low Earth Orbit (LEO), DSN, etc.

CT15: Unified trajectory and link analysis tool for LEO

CT16: Augmentation for deep space

CT17: Augmentation for planetary surfaces

A spectrum analysis tool is needed that will assist designers in predicting communications performance for LEO and deep space applications that is aimed at providing analysis support as well as assistance in preparing data for spectrum applications. This tool could be seen as a product that calls a commercial product such as Satellite Tool Kit for underlying computations for orbits and access. It would also provide supplementary computations needed for the analysis, such as DSN interference estimates, ITU surface power constraint estimates, etc.

C&T Revolutionary Concepts

CT19: Quantum keying

CT20: Superconducting Quantum Interference Filter (SQIF)

CT21: X-ray communications

CT22: Quantum communications

From OCT – TA05: Advancement of X-ray navigation using X-ray emitting pulsars could provide the ability to autonomously determine position anywhere in the solar system just as GPS does for Earth inhabitants. Successful development of SQIF technology would change the paradigm for RF communication to detecting the magnetic field instead of the electric field and provide magnitudes of improvement in our communication systems.

Human Interface Technology
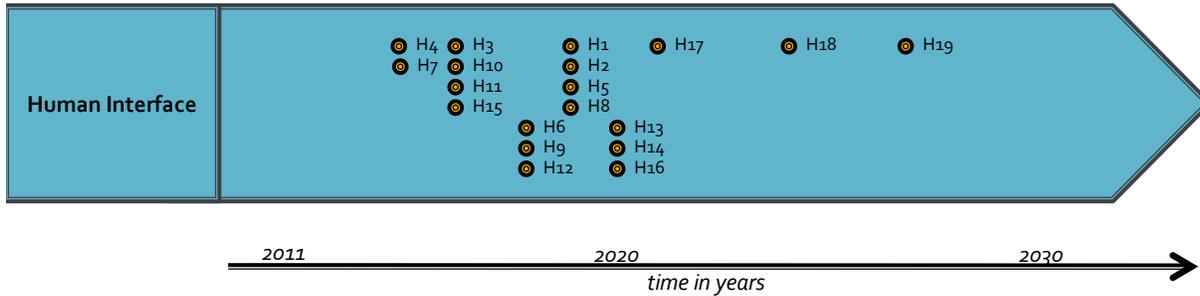
Figure 7. Human Interface Technology timeline.

Computer-Human Interface is an interdisciplinary field which is focused on the interaction between human users and computer systems including the user interface and the underlying processes which produce the interactions. From the human perspective, interaction with the world around us is achieved through our five senses: hearing (auditory interfaces), touch (tactile interfaces), sight (visual interfaces), smell (olfactory interfaces) and taste (gustation interfaces). Olfactory and gustation interfaces have not been included in this roadmap because they are extremely immature technologies and it is unclear which discipline area will implement these types of interfaces (electrical, chemical, etc).

Auditory Interface Technologies

H1: Miniaturized space-qualified microphones

H2: Miniaturized space-qualified speakers

Several technologies are under development which will miniaturize microphones and speakers and allow applications in new contexts. For example, development of distributed planar array microphones, coupled with MEMS technology, will facilitate ubiquitous voice communications without use of crew-worn or hand-held microphones. Also, customization of commercial bone conduction technology for use with traditional dynamic and electret microphones will improve voice communications and speech recognition. As for speakers, implementation of edge vibrated and distributed mode technology will produce low mass, low power, and space efficient loud speakers.

H3: Speech/voice recognition algorithms

H4: Speech-to-text/text-to-speech algorithms

Development of accurate speech recognition technology capable of adapting to physiological effects of spaceflight on the human vocal tract is required. This area includes development of a redundant speech recognizer for reliable voice control of systems. Additionally, optimization of speech-to-text/text-to-speech technology is required to support low data rate/high latency communication links. This technology will improve

space-to-ground communications on high latency links by providing textual conversion of dialog and can be used for real-time dictation in flight. This will include computer speech.

Tactile Interface Technologies

H5: Physiological Computing (PC)

PC is a term used to describe any computing system which uses real-time physiological data as an input stream to control the user interface. The most basic PC is one which records a signal such as heart rate and displays it to the viewer via a screen. Other systems, such as brain-computer interfaces or unvoiced speech recognition, take a stream of physiological data (electrical activity from the brain or muscles) and convert it into input control at the interface, e.g., to move a cursor or select a command. Other types of PC simply monitor physiology in order to assess psychological states and trigger real-time adaptation. For example, if the system detects high blood pressure, it may assume the user is experiencing high frustration and offer help. The applications for PC range from adaptive automation in an aircraft cockpit to computer games where electrical activity is used to initiate particular commands.

H6: Computer haptics

Haptics is a highly interdisciplinary technology area which aims to define how humans and machines touch, explore, and manipulate objects in real, virtual, or teleoperated worlds. Haptics have been used to allow teleoperators to feel what a robot touches and to increase realism in training applications. Flight simulators equipped with force feedback joysticks provide a convincing example for the importance of simulation technology and the significant role haptics play in training. Just as flight simulators are used to train pilots nowadays, it is, for example, anticipated surgical simulators will be used to train physicians in the near future. Moreover, several studies in the past have shown the significance of haptics in teleoperation tasks in real and virtual worlds. For example, artificial force fields not only enable us to train the human operator in virtual environments, but also help him or her execute the teleoperated task better and faster in the real world.

Significant progress has been made in haptics, but there are still many research questions waiting to be answered. One of the constant challenges in integrating haptics into virtual environments is the need for a variety of haptic devices with the requisite degrees of freedom, range, resolution, and frequency bandwidth, both in terms of forces and displacements. Another area of hardware design which requires further investigation is multifingered haptic devices and tactile displays. It has been demonstrated, as we gather information about the shape and size of an object through touch, our fingers and hand move in an optimal manner. Moreover, robotics studies show at least three fingers are necessary for stable grasp. On the other hand, there are only a few multifingered haptic devices which are commercially available today.

Visual Interface Technologies

H7: Two-Dimensional (2D) displays

Traditional 2D displays are constantly evolving. The next generation of these visual displays appears to be Organic Light-Emitting Diode (OLED) technology which significantly reduces size, weight, and power requirements for visual displays. Also, depending on the application, e-Ink displays could have similar benefits. However, other technologies are emerging which could have impact beyond OLED, such as quantum dot, bistable, and laser-phosphor displays.

H8: Autostereoscopic displays

Autostereoscopic displays are able to provide binocular depth perception without the hindrance of specialized headgear or filter/shutter glasses. At its simplest, this is 3-D television (3DTV). However, the technology is also progressing toward digital holographic prints and video. Some of the various technologies which are competing to best implement an autostereoscopic display are parallax barrier, lenticular, volumetric, electro-holographic, and light field displays.

H9: Transparent and deformable displays

Additional layers of capability which are being added to display technologies are transparency and deformation. These capabilities lead toward development of more useable near-to-eye displays, as well as new ways to unobtrusively integrate displays into the environment. These capabilities are being explored through traditional 2D-type displays, as well as through projection and printable displays.

H10: Near-to-Eye Display (NED)

NEDs have been classified into one of three categories based on the mode of image presentation. Monocular NEDs usually have only one display; in binocular (stereo) NEDs, two disparate images are presented on two displays; in bi-ocular mode the same image is presented on two displays. Different types of NED are beneficial for different applications. Two of the most impactful applications of NEDs are virtual reality (presenting an entirely virtual world to the user) and augmented reality (presenting digital information onto the real world).

H11: Panoramic motion imagery acquisition

Panoramic image acquisition is based on mosaic approaches developed in the context of still imagery. Mosaics are created from multiple overlapping sub-images pieced together to form a high-resolution, panoramic or wide field-of-view image. While still imagery mosaics and panoramas are common, high-resolution real-time panoramic video is an emerging area. For panoramic, real-time HD video, an array of video cameras view the scene, while a digital recording and playback system maintains precise frame synchronization, allowing the frames to be stitched together. The challenges encountered in this process span issues

in camera calibration, image processing, compression, networking, computer graphics, and high-performance computing.

H12: Radiation-tolerant HD imagers

The image sensors used for spaceflight applications have historically been commercially available sensors which are vetted through radiation testing on the ground and flown for a limited lifetime until they degrade to a predetermined limit. Then, they are discarded and replaced. For long-duration missions beyond LEO, radiation-tolerant high-definition imagers will be required.

H13: Efficient HD motion imagery compression

Motion imagery compression reduces the amount of data used to represent digital video images, and combines spatial image compression and temporal motion compensation. Most video compression is lossy — it operates on the premise much of the data present before compression is not necessary for achieving good perceptual quality. Some forms of data compression are lossless. This means the data is decompressed, resulting in a bit-for-bit perfect match with the original. While lossless compression of video is possible, it is rarely used, since lossy compression results in far higher compression ratios at an acceptable level of quality. However, in spaceflight applications where very few or no humans are present, video is the primary method we have to experience the mission environment. Future NASA missions will require higher compression ratios without sacrificing image quality.

H14: Computer vision

Computer vision is the field concerned with the automated processing of images from the real world to extract and interpret information on a real-time basis. It is the science and technology of machines which see. Here, "see" means the machine is able to extract information from an image, to solve some task, or perhaps understand the scene in either a broad or limited sense. The field includes scene reconstruction, event detection, video tracking (3D human body tracking, including eye/gaze tracking, object recognition, learning, indexing, motion estimation and image restoration).

H15: Computer-mediated reality

Computer-mediated reality refers to the ability to add or subtract information or otherwise manipulate one's perception of reality through the use of a wearable computer or hand-held device. Typically, it is the user's visual perception of the environment which is mediated. This is done through the use of some kind of electronic device which can act as a visual filter between the real world and what the user perceives. The field of computer-mediated reality encompasses augmented reality (adding or subtracting digital information to the real world) and virtual reality (immersion into a completely digital world).

Multi-Sense Interface Technologies

H16: Electronic Textiles (e-Textiles)

E-textiles are fabrics which have electronics and interconnections woven into them offering physical flexibility and size which cannot be achieved with existing electronic manufacturing techniques. Components and interconnections are intrinsic to the fabric and thus are less visible and not susceptible to becoming tangled or snagged by the surroundings. An e-textile can be worn in everyday situations where currently available wearable computers would hinder the user. E-textiles can also more easily adapt to changes in the computational and sensing requirements of an application, a useful feature for power management and context awareness.

H17: Virtual window

A virtual window utilizes digital technology to simulate an optical window including the changes in perspective due to the movements of the observer. The ultimate implementation would include autostereoscopic video/displays, panoramic motion imagery acquisition, ambiance audio, pan/tilt/zoom for situational awareness, and radiation tolerant video and graphics.

H18: Telepresence

Telepresence refers to a set of technologies which allow a person to feel as if he or she were present, to give the appearance of being present, or to have an effect via telerobotics at a place other than his or her true location. Telepresence requires the user's senses be provided with stimuli to give the feeling of being in the other location. Additionally, the user may be given the ability to affect the remote location. In this case, the user's position, movements, actions, voice, etc., may be sensed, transmitted, and duplicated in the remote location to bring about this effect. Therefore, information may be traveling in both directions between the user and the remote location.

H19: Immersive environment

An immersive digital environment is an artificial, interactive, computer-created scene or world within which a user can immerse one's self. Immersive digital environments could be synonymous with virtual reality without the implication actual reality is being simulated. An immersive digital environment could be a model of reality but it could also be a complete fantasy user interface or abstraction as long as the user of the environment is immersed within it. The definition of immersion is wide and variable but here it is assumed to simply mean the user feels like he or she is part of the simulated universe. The success with which an immersive digital environment can actually immerse the user is dependent on many factors such as believable 3D computer graphics, surround sound, interactive user input, and other factors such as simplicity, functionality, and potential for enjoyment. To create a sense of full immersion, the five senses (sight, sound, touch, smell, taste) must

perceive the digital environment to be physically real. Immersive technology can perceptually fool the senses through:

- Panoramic 3D or holographic displays (visual)
- Surround sound acoustics (auditory)
- Haptics and force feedback (tactile)
- Smell replication (olfactory)
- Taste replication (gustation)

Some potential applications for an immersive environment include crew recreation, training, and troubleshooting.

Acronyms

2D	Two-Dimensional
3-D	Three-Dimensional
ASC	Avionics Steering Committee
ASIC	Application-Specific Integrated Circuit
C	Celsius
C&DH	Command and Data Handling
CMOS	Complementary Metal-Oxide Semiconductor
COMSEC	Communications Security
DARPA	Defense Advanced Research Projects Agency
DDR	Double Data Rate
DRM	Design Reference Mission
DS	Deep Space
DSN	Deep Space Network
DTN	Delay-Tolerant Network
DTRA	Defense Threat Reduction Agency
EVA	Extravehicular Activity
FeRAM	Ferroelectric Random-Access Memory
FPGA	Field Programmable Gate Array
GaN	Gallium Nitride
Gb/s	Gigabits Per Second
GPS	Global Positioning System
HD	High Definition
I/O	Input/Output
ISHM	Integrated System Health Management
ISS	International Space Station
IVHM	Integrated Vehicle Health Management
krad	Kilorad

LEO	Low Earth Orbit
Mb/s	Megabit Per Second
MEM	Microelectromechanical
MIT	Massachusetts Institute of Technology
MPCV	Multi-Purpose Crew Vehicle
MRAM	Magnetoresistive Random Access Memory
NEA	Near Earth Asteroid
NED	Near-to-Eye Display
nm	Nanometer
NRO	National Reconnaissance Office
OCT	Office of the Chief Technologist
OLED	Organic Light-Emitting Diode
phy	Physical
PC	Physiological Computing
PCRAM	Phase-Change Random-Access Memory
RAM	Random Access Memory
QML	
RF	Radio Frequency
RFID	Radio Frequency Identificaiton
RH	Radiation Hardened
RHBD	Radiation Hardening By Design
SAW	Surface Acoustic Wave
SBC	Single Board Computer
SDRAM	Synchronous Dynamic Random Access Memory
SiGe	Silicon-Germanium
SiC	Silicon Carbide
SIMD	Single Instruction Multiple Data
SLS	Space Launch System
SOC	System On Chip
SOI	Silicon-On-Insulator

SONOS	Silicon-Oxide-Nitride-Oxide Silicon
SQIF	Superconducting Quantum Interference Filter
SRAM	Static Random Access Memory
THz	Terahertz
TRL	Technology Readiness Level
TSV	Through Silicon Via
μm	Micrometer

REPORT DOCUMENTATION PAGE

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
01- 04 - 2013	Technical Memorandum	

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Flight Avionics Hardware Roadmap	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)	5d. PROJECT NUMBER
Hodson, Robert F.; McCabe, Mary; Paulick, Paul; Ruffner, Tim; Some, Rafi; Chen, Yuan; Vitalpur, Sharada; Hughes, Mark; Ling, Kuok; Redifer, Matt; Wallace, Shawn	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
NASA Langley Research Center Hampton, VA 23681-2199	L-20245

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
National Aeronautics and Space Administration Washington, DC 20546-0001	NASA
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)
	NASA/TM-2013-217986

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 33
Availability: NASA CASI (443) 757-5802

13. SUPPLEMENTARY NOTES

14. ABSTRACT

As part of NASA's Avionics Steering Committee's stated goal "to advance the avionics discipline ahead of program and project needs," the committee initiated a multi-Center technology roadmapping activity to create a comprehensive avionics roadmap. The roadmap is intended to strategically guide avionics technology development to effectively meet future NASA missions' needs. The scope of the roadmap aligns with the twelve avionics elements defined in the ASC charter, but is subdivided into the following five areas: Foundational Technology (including devices and components), Command and Data Handling, Spaceflight Instrumentation, Communication and Tracking, and Human Interfaces.

15. SUBJECT TERMS

Avionics; Hardware; Roadmap

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			STI Help Desk (email: help@sti.nasa.gov)
U	U	U	UU	40	19b. TELEPHONE NUMBER *(Include area code)* (443) 757-5802