An Overview of the Current State of the Art on Small Spacecraft Avionics Systems

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Small spacecraft command and data handling and flight software systems, technologies, and capabilities are continuously evolving, enabling new opportunities for developing and deploying next-generation small spacecraft avionics. When small spacecraft were first introduced, their primary purpose was to observe and send information back to Earth. As awareness and utility expands, there is a need to improve the overall capability of collecting data in a specific mission environment. Small spacecraft currently perform a wide variety of science in low-Earth orbit and are emerging as candidates for more formidable beyond low-Earth orbit missions. This paper will expand on the technological evolution of avionics systems, their requirements to meet the need for modern, complex small spacecraft missions, and the updated avionics architecture composition. The authors will also inform the readers on the current state-of-the-art in SmallSat avionics and connect decentralized avionics architecture to non-aerospace applications and its underlying role in the movement to "digitally managed everything".

I. Introduction

The development of avionics systems for future, complex small spacecraft ("SmallSat") mission operations beyond Earth environments requires a modernized optimization and standardization effort. Spacecraft avionics are defined as all electronic subsystems, components, instruments, and functional elements included in the spacecraft platform. These primarily include the flight subelements, command and data handling (C&DH) and flight software (FSW); specialty flight subsystems including payload data; control processors, and electronics. All must be configurable into specific mission platforms, architectures and protocols, and governed by appropriate development environments, standards, and tools. A spacecraft's C&DH and FSW are considered the brain and nervous system of the integrated avionics suite. They generally provide command, control, communication, and data management interfaces with all other subsystems in some manner, whether in a direct point-to-point or distributed computing mode. The FSW is, at a fundamental level, the instruction set for the spacecraft to perform all operations necessary for the mission. These include all the science objectives as regular tasks (commands) to keep the spacecraft functioning and ensure the storage

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and communication of data (telemetry). The FSW is usually considered to be the code that runs on the C&DH avionics but should also include all software code running on the various subsystems and payload(s). As C&DH components and factors become more capable, this in turn has increased demands and requirements on FSW. As the nature of the mission influences the avionics architecture design, there is a large degree of variability in any avionics system.

Traditional spacecraft avionics have generally been designed around centralized architectures where each subsystem relies on a single processor, thus if one element fails, then the entire architecture commonly fails. This design often results in increased mass, high-power consumption, large volume, complex interfaces, and weak system reconfiguration capabilities. An open, distributed, and integrated avionics architecture with modular capability in software and hardware design is becoming more appealing for complex spacecraft development needs. In anticipation of extended durations in low-Earth orbit (LEO) and deep space missions, vendors are now incorporating radiation hardened or radiation-tolerant architecture designs in their SmallSat avionics packages to further increase their overall reliability. A driving trend in aerospace is the utilization of SmallSats to perform complex space science, and thus SmallSat technology, primarily the avionics system, must mature to meet the robust, future needs of anticipated lunar and deep space science SmallSat missions.

This paper leverages information from the "Small Spacecraft Avionics" chapter in the *2021 State-of-the-Art Small Spacecraft Technology* report. The organizational approach of this paper is as follows: the authors will provide a brief history of SmallSats and their pioneering evolution in aerospace to introduce the reader to this platform classification; identify the technological evolution of avionics systems, their requirements to meet the need for modern, complex SmallSat missions, and the updated avionics architecture composition; expand on the current state of the art in SmallSat avionics; and highlight their value in non-aerospace applications.

II. History and Evolution of Small Spacecraft

Before the 21st century, larger spacecraft with mass >1000 kg were the main option to access space and it was common for spacecraft to be considered "small" if their total mass was under 1000 kg. This large mass requirement combined with the desire to perform physics, geophysics, heliophysics, and astrophysics investigations from space quickly became associated with exceedingly high cost and long-term mission development. To address the considerable mass, substantial cost, and low-launch cadence, National Aeronautics Space Administration (NASA)'s Science Mission Directorate (SMD) initiated the Explorers Program to provide reasonable flight opportunities for relatively small spacecraft missions. NASA's SMD established the Small Explorer (SMEX) Program in 1988 to encourage the development of SmallSat missions that could be quickly developed at relatively low cost [1]. This decrease in spacecraft mass and increase in science capabilities ignited interest in miniaturization and maturity of aerospace technologies that have proven capable of producing missions for less cost with a high turn-over rate. This continuous expansion of the space industry has matured towards a standardization that can satisfy the needs of multiple customer bases and missions, and this has resulted in the acceptance of the smaller spacecraft platform commonly referred to as nanosatellites.

A. SmallSat Categories

Spacecraft are generally regarded as large or small and are further categorized according to a specific mass allocation. Table 1 below differentiates the commonly accepted spacecraft definitions in the aerospace industry. Formal SmallSat classifications tend to adhere to the five listed categories though the upper limit for a "mini spacecraft", or "minisatellite", tends to vary from 180 – 500 kg while the smaller spacecraft (micro – femto) definitions are more ubiquitously accepted. For the purposes of this paper, the authors will focus on minisatellite – nanosatellite and will use the 180 kg upper mass limit. For higher launch cadence at lower cost, the nanosatellite was initially for academic and research purposes, and the "CubeSat" was the first standardized nanosatellite platform. The CubeSat concept initiated from a collaboration between California Polytechnic State University (Cal Poly) in San Luis Obispo and Stanford University in Stanford, California, in 1999.

Table 1. Formally Designated Spacecraft Class Categories

Spacecraft Class Category		Wet Mass (kg)
Large Spacecraft		>1000
Small Spacecraft	Medium Spacecraft	500 – 1000
	Mini Spacecraft	100 – 500*
	Micro Spacecraft	10 – 100†
	Nano Spacecraft	1 – 10†
	Pico Spacecraft	0.01 – 1
	Femto Spacecraft	0.01 – 0.1

*Organization-dependent upper thresholds vary from 180 – 500 kg

†CubeSats fall under both of these mass definitions

CubeSats are now a common SmallSat form that can weigh from only a few kilograms up to 30 kg and are based on a form factor of a 10 cm square cube, or unit (U) shown in Fig. 1. Larger CubeSat sizes are becoming increasingly popular and standardized as they offer researchers new opportunities for studying space science due to their standardized launch vehicle interfaces, additional volume, power, and the fact that they provide an overall increase in capability at a fraction of the cost of a large spacecraft. NASA's Space Technology Mission Directorate and NASA SMD's Heliophysics, Astrophysics, Earth, and Planetary Science divisions have all funded and flown SmallSat and CubeSat science missions and are expected to continue to use these small spacecraft for future space science missions [2].

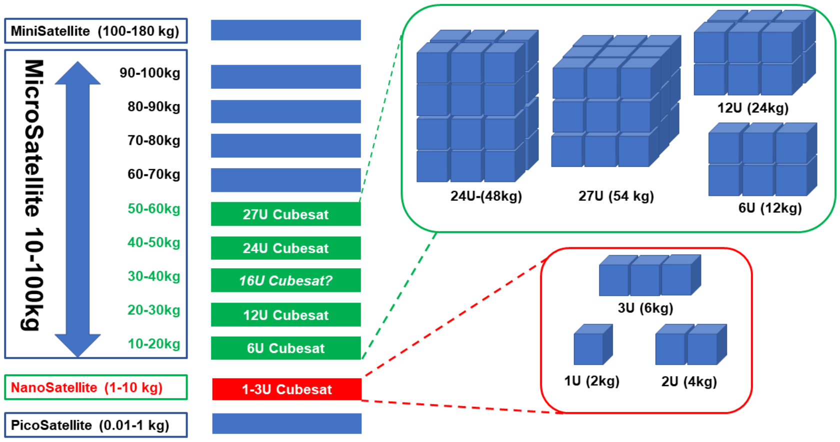

Fig.1 Nanosatellite sizes compared to CubeSat containerized sizes. Credit: NASA.

SmallSats, particularly nanosatellites, are notorious for their design constraints of low-cost, low-mass, low-power, and low-volume, and are typically passive in terms of propulsion and thermal control. The past decade of the high market production of nanosatellites has motivated the miniaturization and performance enhancement of subsystem technology to meet these constraints and allow the collection of more data. This evolution of SmallSat technology has resulted in higher capability in the same small size, and this increased capability relies on the design of the maturity of the avionics and electronics. Avionics and electronics design have been very mission dependent, and there is a natural division between SmallSats and CubeSats where the avionics architecture shifts and requires different avionics configurations. Part of this is driven by the life/reliability requirement (redundancy) and the weight/support requirements of the subsystems – sensors/actuators including wheels and star-trackers, propulsion, thermal control, and communication architecture.

B. SmallSat Missions

When SmallSats were first introduced, they primarily served as technology demonstrators, educational platforms, and risk reduction science missions that observed and sent information back to Earth. These basic space mission functions relied on simple subsystem components – a communication transceiver, solar panels, magnetorquer, deployable antenna, a microcontroller, and some form of payload, whether a bus subsystem technology maturation or a science or research instrument. As SmallSat awareness and utility expand beyond this, there is a need to improve the overall capability of collecting larger amounts of data in a specific mission environment – thus increasing the complexity of the avionics system. SmallSats currently perform a wide variety of science in LEO and are emerging as candidates for more formidable beyond-LEO missions. Common SmallSat missions include remote sensing, multipoint *in-situ* measurements, space weather, technology demonstrations, and now have a presence in commercial utilization for broadband internet and Internet of Things (IoT) communication infrastructure. The increased complexity of a SmallSat mission will heighten in the anticipation of the collection of lunar and deep space science, and SmallSat avionics technology must continue to evolve to meet these needs.

Modern space applications now require considerable autonomy, precision, and robustness, and are beginning to incorporate refined technologies for in-orbit servicing, relative and absolute navigation, intersatellite communication, and formation flying. In parallel, spacecraft electronic components have matured to have higher performance, high reliability, and can be miniaturized to meet the growing needs of these now very capable spacecraft. A known limitation is that SmallSat technology is often inadequate for deep space mission operations, primarily due to the lack of robustness in the flight computer, and is a major drawback for deep space SmallSat missions. SmallSat C&DH and FSW systems, technologies, and capabilities have been continuously evolving, enabling new opportunities for developing and deploying next-generation SmallSat avionics. The placement and configuration of the avionics are driven by the size, shape, and thermal characteristics of the spacecraft, and it is often the case where the iterative avionics design has to be reshaped to meet the needs of the other vehicle's operational requirements [3].

III. Modern Avionics Evolution

The traditional centralized avionics architecture with a single processor is not always a reliable method for future space flight missions. If any component of this architecture were to fail on orbit, the entire mission operation collapses. Next generation avionics systems will integrate most of the electronic equipment on the spacecraft and an avionics system designed with networked real-time multitasking distributed system software. This capability can implement dynamic reconfiguration of functions and task scheduling and improves the failure tolerance that may minimize the necessity of expensive radiation-hardened electronic components. Requirements for an improved avionics composition include [3]: (1) high-performance computing hardware to handle the large amount of anticipated data generated by the more complex SmallSats, (2) embedded system software networked for real-time multitasking distributed system software for on orbit reconfiguration and updates (also known as re-programmability), (3) software partition protection mechanisms to control additional hazards, or faults, created in a design or implementation that may affect the operations of other functions that share resources, and (4) the avionics and electronics suite must be robust enough to handle the large amounts of radiation in deep space for a longer period of time. This improved performance in the same spacecraft package puts considerable expectations on the avionics, and it cannot be efficiently achieved with a centralized architecture. A distributed, heterogeneous configuration can provide these capabilities for future, complex SmallSat missions. Distributed computing systems are common in aviation, automotive, and other industries, though are a relatively recent addition to spacecraft bus design.

With the implementation of a heterogeneous, distributed architecture in mixed criticality configurations, systems contain multiple processors with varying levels of performance and capabilities. Mixed criticality management enables a system to execute different applications of varying levels of criticality and promotes system modularity of task attribution [3]. This enables standardization and distribution of data communication protocols, error-handling, and C&DH interface, and allows for component-level modularity, simplified collaborative processing and effective control over specific subsystems, data sharing capabilities, and subsystem redundancy and low power. Ultimately, a distributed avionics architecture will simplify "the command and data flow within the satellite by clarifying which specific component is responsible for each task and what information exchange is required to initiate the task" [5]. Some systems are now designed with this configuration capability to achieve these requirements for improved avionics composition and some are still not suitable for SmallSats in deep space.

Low-power, high-performance processors that can manage the large amount of generated data are equipped to be more efficient for reducing on-board energy and their reduced power allows for more passive cooling in the tightly packaged spacecraft [6]. This is useful for current complex SmallSat missions, such as multi-spacecraft missions, e.g. swarms and constellations, and for future complex SmallSats that will venture into deep space. Significant advances in inter-satellite communication (such as laser cross-link and use of high frequency bands) have improved the amount of generated data and minimized latency in data collection. Low-power **A**dvanced **R**educed Instruction Set Computer **M**achine (ARM)-based processors already have extensive terrestrial applications, and the next step is to ensure its radiation hardened and/or redundancy characteristics for deep space. System developers are gravitating towards open source, ready-to-use hardware and software development platforms that can provide seamless migration to higher performance architectures. As with non-space applications, there is a reluctance to change controller architectures due to the cost of retraining and code migration.

A software defined radio can transmit and receive in widely different radio protocols based on a modifiable, reconfigurable architecture, and is a flexible technology that can "enable the design of an adaptive communications system" [6]. The integration of Field Programmable Gate Array (FPGA) software-defined radios on SmallSats is a recent addition and is shown to increase data throughput and provide the ability for software updates on orbit (re-programmability). The ability to reprogram sensors or instruments while on orbit has benefited several CubeSat missions whose instruments did not perform as anticipated or they entered into an extended mission and needed to reprogram subsystems or instruments quickly [3]. It should be noted that the most advanced FPGAs are not yet designed for space, but there are mitigations for space implementation. These mitigations include redundant subelements, internal triple voting of circuits or functions, periodic scrubbing of the FPGA programming code, and periodic, refresh and reset techniques.

As in aviation, if a space vehicle experiences a design or implementation fault during operations, that would serve as either serious or catastrophic. This key differentiator is whether the fault propagates to another system and causes simultaneous failure or if the fault can be contained (partitioned) such that operations can continue. The propagation of a fault occurs if systems share a processor or some other resource and the characteristics of a distributed system rely on software partition protection. Software partition protection mechanisms control additional hazards, or faults, created in a design or implementation that may affect the operations of other functions that share resources [4]. Software partitions are implemented to handle fault containment in the event a fault occurs in one partition, it is isolated to that partition and does not affect the other partitions in the system.

Another inevitable requirement for modern avionics is the need for the system to be robust enough to withstand the higher radiation environment in deep space and for a longer duration. As SmallSats continue to move from the early CubeSat designs with short-term mission lifetimes to longer missions, selecting parts that are radiation hardened (rad-hard) is important. While rad-hard processors exist and have had extensive testing, the spacecraft is only as radiation tolerant as the whole system. If non-rad-hard supporting electronics fail, then the entire system fails with it. A major tactic used to avoid radiation effects is to turn off the space vehicle (also known as sleep mode) for most portions during its flight in deep space and turn it on for science collection only. With the upcoming launch of Artemis-I, twelve nanosatellites will venture into lunar and deep space and these missions will serve as demonstrations for how their rad-hard avionics suites function. There are a variety rad-hard processors available for SmallSats and several of them are listed in the “Small Spacecraft Avionics” chapter in the *2021 State-of-the-Art Small Spacecraft Technology* report.

IV. State-of-the-Art: SmallSat Avionics

Current trends in SmallSat avionics generally appear to be following those of previous, larger scale avionics subsystems. There are many factors to be considered in the optimum selection, configuration and implementation of avionics subsystems, components, and elements for SmallSat missions. Considerations of particular interest to SmallSat avionics systems in determining the state of the art for the C&DH, FSW, and subsystem/payload specific electronic systems include the following:

- SmallSat Platform Size Ranges and Configurations
- Integrated Avionics Platform Architectures
- Mission Avionics Configurations
- Spacecraft and Mission Autonomy

The information in this section provides details on state-of-the-art SmallSat avionics drawn from the “Small Spacecraft Avionics” chapter in the *2021 State-of-the-Art Small Spacecraft Technology* report. This chapter partitions SmallSat avionics into C&DH and FSW, and in this paper this section will follow suit. Within the report, the application of the NASA Technology Readiness Level (TRL) scale is used to objectively evaluate and confirm technologies as state of the art (TRL 5-9), and the developmental approaches that support the TRL maturation of a particular technology are identified and reviewed. For a more detailed description of specific SmallSat avionics technology, the reader is encouraged to read the chapter.

C. State-of-the-Art: Command and Data Handling

The current generation of microprocessors can easily handle the processing requirements of most C&DH subsystems and will likely be sufficient for use in spacecraft bus designs for the foreseeable future. Cost and availability are likely primary factors for selecting a C&DH subsystem design from a given manufacturer. The ability to spread non-recurring engineering costs over multiple missions, and to reduce software development through reuse, are desirable factors in a competitive market. Heritage designs are desirable for customers looking to select components with proven reliability for their mission. With the increase in processing capability with C&DH and other processors, more capabilities have been enabled with FSW. Table 2 lists C&DH components and factors, and schemes taken into account for SmallSat application.

Table 2. Command and Data Handling Components and Factors

Characteristic	**Implementation**
Highly Integrated On-Board Computing Products	CompactPCI and PC/104 form factors continue generally to be the industry standard for CubeSat C&DH bus systems.
Radiation-Hardened Processors and Field Programmable Gate Arrays (FPGA)	A variety of vendors are producing highly-integrated, modular, on-board computing systems for small spacecraft. These C&DH packages combine microcontrollers and/or FPGAs with various memory banks, and with a variety of standard interfaces for use with the other subsystems on board.
Memory, Electronic Function Blocks, and Components	A variety of different memory technologies have been developed for specific traits, including Static Random Access Memory (SRAM), Dynamic RAM (DRAM), flash memory (a type of electrically erasable, programmable, read-only memory), Magnetoresistive RAM (MRAM), Ferro-Electric RAM (FERAM), Chalcogenide RAM (CRAM) and Phase Change Memory (PCM).
Bus Electrical Command and Data Interfaces	Highly integrated systems will typically provide several interfaces to accommodate a wide range of users and to ease the task of interfacing with peripheral devices and other controllers.
Radiation Mitigation and Tolerance Schemes	Techniques used to mitigate system failures caused by radiation effects. CDH element areas of consideration include: memory, imaging, protection circuits (watchdog timers, communications watchdog timers, overcurrent protection, periodic refresh/resets, and power control), memory protection (error-correction code memory and software error detection and correction), communication protection (several components), and parallel processing and voting.

The modern integrated space avionics, i.e., heterogeneous and mixed criticality architectures, have an impact on the nature and operational constructs, and can contribute to advanced configurations such as Multiple Modular Redundant systems architectures which can allow advanced paradigms for radiation tolerance and system redundancies in critical SmallSat missions. Advances in processing capability, such as low-power ARM-based processors and improved radiation hardened processors, have brought similar processing capabilities down to the small size of CubeSats.

Many C&DH systems will continue to follow trends set for terrestrial embedded systems. Short duration missions in LEO will continue to take advantage of advances made by industry leaders who provide embedded systems, technologies, and components. In keeping with the low-cost, rapid development theme of CubeSat-based missions, many commercial-off-the-shelf (COTS) solutions are available for spacecraft developers. While traditional C&DH processing needs are relatively stagnant, as SmallSats are being targeted for flying increasingly data-heavy payloads, e.g. imaging systems, there is new interest in advanced on-board processing for mission data. Typically, these higher performance functions would be added as a separate payload processing element outside of the C&DH function.

D. State-of-the-Art: Flight Software

Flight software complexity refers to the number of operations to be performed and is not based on the size of the spacecraft, only the overall requirements and mission objectives. The more software is required to do, the bigger the task and cost. This complexity (and the associated verification effort) is what primarily drives the cost and schedule for the program or mission. Required reliability and fault management can also increase complexity and cost, regardless with FSW. As FSW must operate in a real-time environment, C&DH and other subsystems need to be performed in a reliable and predictable fashion throughout the lifetime of the mission.

Naturally, there are C&DH processor functionality implications on FSW. The processor and memory available on the C&DH significantly limit and increase demands and requirements on FSW. For more routine, high reliability SmallSat missions and to reduce electronic complexity in general, smaller processors are used in a heterogenous architecture configuration. Experimental, or technology demonstrator, SmallSat missions typically focused on low-cost, easy-to-develop systems, take advantage of open-source software and hardware and provide an easy entry into space systems development. This is of particular interest for hobbyists or those who lack specific spacecraft expertise. Significant differences in mission requirements between short-term experimental missions and long-term high reliability missions can impact how state-of-the-art is perceived for flight units. Software code and programs are very integrated with the hardware, requiring careful implementation and integration. Software development environments for these kinds of processors usually come from the microprocessor vendors themselves, or from third party vendors. Several vendors have large processors that can run on a variety of Real-Time Operating Systems (RTOS), such as VxWorks, Real-Time Executive for Multiprocessor Systems (RTEMS), FreeRTOS, and Linux. A major benefit here is that some operating systems are open-source which enables further utilization on space and aviation operations.

In other instances, functionality is distributed between a large capability processor and a smaller dedicated flight controller whereby the controller conducts and manages the real-time aspects, allowing efficient management of power and operational complexity. These give software developers a significant advantage with a software development environment and usually a base implementation on the processing target. Table 3 below provides an overview on FSW in context for SmallSat avionics.

Table 3. Flight Software in context of SmallSat Avionics

Software Function	**Products**
Frameworks: a hierarchal systems-of-systems architecture, sometimes described as a set of Lego-like building block constructs, partitions, and functions.	core Flight Software Systems (cFS), open-sourced F Prime (F’), released under the Apache 2.0 license SpaceCloud, Robot Operating System (ROS or ros), open-sourced
Operating Systems: System software that manages computer hardware, software resources, and provides common services for computer programming.	VxWorks FreeRTOS (Real-Time Operating Systems) Linux Debain
Software Languages: System programming involves designing and writing computer programs that allow the computer hardware to interface with the programmer and the user, leading to the effective execution of application software on the computer system (Techopedia).	C C++ Python Arduino Assembly Language

The Robot Operating System (ROS) framework is an open source and modular architecture known for robotics operations has only recently been adopted for aerospace purposes. ROS foundations are an efficient multiprocessing architecture that can establish communication between multiple software modules and is known for its modularity, reusability, and multi-lingual characteristics [7]. The first flight implementations of ROS in spacecraft FSW architecture were used in two CubeSat platforms: the Drag De-Orbit Device (D3) and PAssive Thermal Coating Observatory Operating in Low earth orbit (PATCOOL). These missions validated the reusability of this software and the core functionality contained within, and the reader is encouraged to view specific details found in Ref. 7.

Frameworks that have accrued more development, testing, and validation on both larger and smaller space vehicles are NASA frameworks core Flight Software Systems (cFS) and F Prime (F’). Developed at NASA’s Goddard Space Flight Center, the cSF framework was designed as a reusable, platform-independent software product line to make the avionics architecture accessible to a range of missions from low-cost technology demonstrators to major science missions [8]. Requests to use cFS on future aerospace applications by NASA centers and commercial space agencies is steadily growing. Space vehicles such as the Lunar Reconnaissance Orbiter (LRO), Morpheus Lander, and Lunar Atmosphere and Dust Environment Explorer (LADEE) implemented cFS. SmallSats and CubeSats have also used cFS services and applications with minor project-specific configuration changes. F’ was developed at NASA’s Jet Propulsion Laboratory with small-scale flight systems and instruments in mind. Key features of this framework are the high degree of modularity, software reusability, complete FSW development ecosystem, and the functionality on a wide range of processors and operating systems. The 6U CubeSat mission, Arcsecond Space Telescope Enabling

Research in Astrophysics (ASTERIA), is functionally a space telescope whose FSW is based on F’ to meet the challenging and constrained budget and timeline needs [9]. Similarly to ASTERIA, 6U CubeSat missions, Lunar Flashlight and Near-Earth Asteroid (NEA) Scout will both use F’ deployments that will run on a single core on top of VxWorks and will adapt the generic F’ components for spacecraft fault protection [9].

The field of software is a very dynamic environment that is continuously evolving. The challenges with flight software usually remain the same regardless of the size of the spacecraft (CubeSat to SmallSat) and are related to the size and complexity of the endeavor. Overall, FSW can be known for scheduling issues and implementation issues especially during integration and test. Temptation of adding additional features is usually present. All these factors can drive up overall complexity and threaten success of FSW and the mission as a whole.

V. Non-Aerospace Applications

Improvements to both the distributed and integrated nature of avionics systems have allowed SmallSats to use less hardware and power, increased redundancy, and enabled more efficient and capable space missions on smaller platforms. The miniaturization, low-power, and mixed-criticality aspects of these evolved avionics systems have provided solutions for a wide variety of issues. The higher performance modules and components can be used for advanced data processing, artificial intelligence software integration, and improved mission autonomy. This allows lower performance onboard processors and FPGAs to both better conduct routine spacecraft functions and interact with unique subsystems.

This continued evolution of SmallSat avionics has benefited by two major development paths: 1) the creation of incredible 21st century tools, technologies, and approaches that are being increasingly considered in spacecraft development and deployment for their next-generation capabilities, and 2) the integrated mission avionics architectures and systems now being increasingly integrated into modern aircraft systems. Additionally, several industries (including biotech, robotics and automation, automotive, and healthcare) have widely benefited from the advancement of these next-generation avionics systems, which will continue to expand as avionics improve. In keeping with the trends seen in other disciplines and industries, both the Industry 4.0 paradigm and a “digitally managed everything” mindset are critically important for improved technological and programmatic efficiencies. One key factor within this Industry 4.0 environment is the ability for decentralized decision-making thereby enhancing task autonomy; a main theme in modern spaceflight avionics architectures. A shift to wireless component-to-component communication and automation of traditional industrial manufacturing started the ‘Internet of Things’ movement, smart technology, and machine-to-machine communication. Coincidently, the low-cost and fast turn-over rate associated with SmallSat missions has enabled these rapid generational advancements – with more emerging applications shown below.

1. Artificial Intelligence, Machine Learning / Machine Vision
2. Smart Sensors
3. Robotics and Automation
4. Model-Based Systems Engineering
5. Embedded Systems / Edge Computing
6. Internet-of-Space-Things
7. Cloud Computing
8. Augmented Reality/ Virtual Reality / Mixed Reality
9. Software-Defined-Everything
10. Advanced Manufacturing
11. Digital Twin

The Mars Helicopter, Ingenuity, successfully integrated and demonstrated the use of COTS hardware and open-source software (such as F’ and cFS) during its successful technology demonstration as a component of the NASA Perseverance Mars Rover mission currently in operation on the Mars surface. cFS provides a foundation for producing an increase in science and technology projects and missions at a rapid rate, and supports new advancements in robotics, Earth and space vehicles such as automobiles, rovers, landers, submarines, ships, military vehicles, rockets, launch vehicles, airplanes and helicopters [8]. The FSW for the upcoming Mars Helicopter mission will use F’ throughout the development of the prototype and actual flight vehicles [9]. Several open-source hardware platforms used in SmallSat missions hold promise for non-aerospace software designs, see Table 4 for a brief list. C&DH solutions have been developed and implemented with built-in FPGAs that have been developed on open-source Linux OS, ultimately broadening the range of developer tool options, from web-based interfaces to Android and Python environments. Not only does this further ease the learning curve for novice developers, but it allows the full power of a Linux system to be harnessed in computation tasks.

Table 4. Open-Sourced Hardware Platforms

Hardware Platform	**Description**
Arduino	Consist of a microcontroller with complementary hardware circuits, called shields. The Arduino platform uses Atmel microcontrollers.
Raspberry Pi	Capable of handling imaging, and potentially, high-speed communication applications and can accommodate core Flight Software and available in multiple demonstrated embodiments.
BeagleBone	Contains ARM processor and supports OpenCV, a powerful open-source machine vision software tool that could be used for imaging applications with embedded-Linux systems running Angstrom.
Xilinx ZYNQ	These systems typically have been developed on open-source Linux OS.
Teensy	A complete USB-based microcontroller development system.

VI. Conclusion

Multi-satellite mission architectures have gained interest and acceptance with higher utility of lower-cost, advanced SmallSat missions. Such configurations described as distributed *ad hoc* constellation networks and swarms, synchronized formations, and other multi-satellite cluster formations, are creating new opportunities for SmallSat avionics. Increased need for synchronization, intersatellite communications, controlled positioning for integrated C&DH functionality, operation of concept of operations and autonomous operations impose new constraints on the avionics system. This not only applies for single satellites, but for systems of systems, whereby overall mission performance is now dependent on all the platform elements acting in a co-dependent fashion, i.e. constellations and swarms.

An exciting trend is that SmallSat missions are becoming more complex in the anticipation of these platforms being used for lunar and deep space science and exploration missions. To achieve the next generational goals of collecting science in deep space using SmallSats, as well as risk mitigation for larger more complex and mission-critical situations, spacecraft electronic components have matured to have higher performance, higher reliability, and miniaturized to meet these growing needs of these now very capable spacecraft. An improved avionics ecosystem is a heterogenous, distributed, and interrelated framework that is now primarily digitally based and or managed. Also, SmallSat avionics should not be considered as an isolated spaceflight technology component, but rather as a core digital engineering technology emphasis area, capable of taking advantage of and integrating products, processes, and technologies from other disciplines. To continue to be relevant and efficient, the SmallSat avionics communities must remain cognizant and receptive of the continuously evolving nature of the digital based Industry 4.0 technology revolution now being evidenced in other related and/or associated vertical disciplines and solutions.

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