Final Research Report

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Abstract. Since the 1950's A.D. humans have sent satellites to orbit to perform a wide variety of missions. Present day satellites are used in several sectors for gathering information or sending signals to vast numbers of consumers. Modern advances and standardization in the satellite industry make access to satellites fairly regular, requiring increasingly reliable embedded systems that can operate autonomously.

1 Introduction

In October of 1957, the first man-made satellite entered orbit and began transmitting a small, simple radio transmission to receivers on the surface of the Earth. Even though the spacecraft was low in complexity it demonstrated the ability to reach space and use tools that can take advantage of an environment that is free of traditional hazards. Shortly after, in January of 1958, the Explorer-1 satellite expanded the use of satellites by becoming the first spacecraft to carry scientific instruments (Rodzi (2022)). Explorer-1 was equipped with a cosmic ray detector, a device used to measure radiation in the Earth's atmosphere and leading to the discovery of a zone of charged particles trapped within the magnetic field, named the Van Allen Belts. Scientific breakthroughs were arising almost immediately from successful satellite deployments and by 1962 the first commercial satellite, Telstar 1, joined the others in orbit. Telstar 1 provided signals for television, telephone, fax, and other devices that were previously restricted by landmarks and geographical barriers, opening doorways for businesses to overcome traditionally costly expenses and expanding the communication capabilities of people on Earth. As of 2022, 6095 satellites were actively in orbit (Sergieieva (2023)), coming from a multitude of nations and with an ever-growing number of applications.

In general, Earth has been surrounded by natural satellites well before the presence of humans, such as the Moon and asteroids, but the focus of this paper will remain on the satellites created by humans and designed for a specific purpose, also known as artificial satellites. Artificial satellites are broadly categorized by the orbital path or distance the satellite holds, such as Low Earth Orbit (LEO), Medium Earth Orbit (MEO), Geostationary Earth Orbit (GEO), Sun-Synchronous Orbit (SSO), and Geostationary Transfer Orbit (GTO). Each category requires a system that is appropriate for the satellite to maintain the orbit is in, whether to maintain the performance of the system or to avoid any position that causes the satellite to deorbit or collide with another object. In addition to the orbital categories, the scope of artificial satellites has uses in many areas, such as government, commercial, scientific, and educational. Embedded systems are indispensable in satellites and space exploration, especially as more fields of interest find use for satellites(TB and AL (2021)). Objects in orbit are difficult to maintain and upgrade without on-satellite embedded systems, requiring costly rocket launches and narrow windows of opportunity to catch the speeding object at the right moment. Embedded systems have enabled satellites to perform minor maintenance as well as upgrading firmware and software, reducing the need for replacing entire satellites while lowering the overall cost of satellites. Aligned with the low cost of advanced computing hardware components and a growing commercial space industry, access to satellite technology has greatly expanded, increasing the need for the development of embedded systems that can operate autonomously and reliably provide data to control centers on Earth.

Application of artificial satellites can vary depending on the operator of the satellite. Commercially, satellites are used for communications, typically in relaying signals for television, telecommunications, and internet connection. Navigation satellites provide position and timing information, such as GPS, and are typically operated commercially or by government entities. Information on weather, traffic, and object monitoring can be relayed from navigation satellites, with some modern approaches implementing Multi-object Tracking algorithms (MOT) to further positioning accuracy (Yu et al. (2025)). Scientific satellites are a category of artificial satellites that have unique embedded systems with specific purposes in collecting data for scientific research. Space telescopes, such as the James Webb Space Telescope (JWST) and Hubble, are a type of scientific satellite that routinely retrieves an immense amount of data from distant light sources. Because of the complexity and size of the data retrieved as well as the latency in transmitting the data from satellite to a ground-based control center, embedded on-satellite systems compose the data into a form that is more desirable for analysis (Zhang et al. (2018)). Since scientific telescopes are typically more advanced and highly specialized, the focus of this paper will remain with the general construct of navigation and commercial satellites.

2 Artificial Satellites

Traditionally, artificial satellites have used many teams that handle various aspects of the design and assembly process, requiring rigorous testing and careful planning to successfully craft a new satellite. After decades of producing satellites, standards and general formats have been developed that are universally accepted and shared among satellite design teams. A large part of the standardization is the need to secure the satellite to the payload fairing so it can be launched and deployed into orbit. Some satellites are designed to fit the restrictions of a dispenser that removes the satellite, however modular satellite structures are becoming popular since they can be secured in the payload fairing using cables (Kongsberg (2023)). The restrictions of the payload fairing are still necessary for designing a satellite, but the number of components a system can use increases when using modular satellite structures.

The general design of satellites includes four components: a main bus, antennas, a power system, and instruments (Tiedeken (2025)). The main bus is the housing for primary electronics and computer modules that direct operations for the system. Antennas are used to send and receive data from ground control and typically transfer low data rates through a flagpole shaped antenna, also known as low-gain antennas. High-gain, parabolic shaped antennas are used on satellites where transfer of high data rates over long distances is necessary, but likely only found in scientific satellites sent to orbit celestial bodies other than Earth. Artificial satellites are most commonly powered by solar panels, often deployed through booms into winglike structures that are stored during launch to prevent damage. Instruments used in satellite systems come in many variants that depend on the intended use of the satellite. Some satellites only require transceivers if information is being relayed through satellite, while others can be used to take measurements through spectral analysis or gravitational forces.

All satellites adhere to rigorous testing standards to ensure the spacecraft can safely make it to space and withstand the environmental extremes while in orbit. Thermal management testing is important to keeping the computational components and batteries from failure since satellites experience a range of 300°C as satellites go from fully exposed to the Sun's rays to being in Earth's shadow (Kongsberg (2023)). In addition to thermal management tests, vibration and acoustic testing are done to test the conditions satellites experience during launch.

3 Embedded Systems in Satellites

Challenges in embedded satellite systems. Embedded systems in satellites combine computational components and peripherals to effectively navigate in orbit around the Earth while managing data and sending information to ground sources. Most satellite embedded systems contain onboard control, navigation, communication, and data processing components housed in the main bus, with associated sensors strategically installed in the structure. While knowledge of satellite systems is fairly standardized, there are challenges embedded satellite systems face need to be considered when designing such as power constraints, radiation exposure, scalability, and data security. Components designed for satellites can be created using radiation hardening, a process that uniquely focuses on the amount of damage components can take from radiation exposure and how to extend the life of the components by using materials resistant to radiation damage, designing circuit layouts to minimize radiation impact, and testing the system for radiation damage to ensure the life expectancy is met. A problem that persists in embedded systems of all manner is power constraints. Power is typically supplied through solar cells on booms that extend from main bus, meaning the system requires batteries to keep the system operating while the satellite is in the Earth's shadow. Since the range of temperature is vast, batteries need to be implemented in a way that prevents overheating of the computing components while the satellite is exposed to the Sun's rays and from freezing while in Earth's shadow on top of being the primary power source during that period. Low heat emitting lithium-ion batteries are used in some satellites along with a battery heater that idles during high temperatures while a battery balancing function dynamically adjusts accordingly. Scalability, as discussed previously, is a concern that cannot be mitigated easily; most of the limitations to scaling the size of a satellite come from the restrictions presented by the payload dispenser and/or payload fairing. Satellites system scalability can be enhanced indirectly by creating a network of satellites called a constellation, where satellites are strategically structured in a pattern that allows the satellite system to operate in a vast area instead of locally. The option of using more satellites can be expensive, however sharing the workload through a constellation of smaller satellites, such as microsats, has proven to be efficient and effective, making it a popular option for financially small operators (Promwad (2025)). Data security is crucial to satellites, not only to keep sensitive information away from malintent but also to ensure the data isn't corrupted from faults while operating in orbit. Real-time operating systems are implemented on satellites for higher software management of a system, giving access to hardware control that helps manage data safely and detect faults in advance. Along with RTOS, field programmable arrays (FPGAs) implement algorithms entirely on satellites that enable a system to perform complex processes. Memory redundancy and fault prevention are easier to do with software functionality presented by RTOS and FPGAs which is why both are becoming more common in satellite systems as electronics get smaller and more reliable.

Example design of a standard satellite embedded system. As mentioned previously, standardizing satellites has benefited the industry immensely, providing guarantees by combining observed successes with past satellite productions. Aside from fitting inside of a payload fairing, structures of a satellite are used to attach the subsystems and satellite payload (if present) as well as deployable instruments attached to booms. Attitude control and propulsion of the system reacts to satellite tumble that can occur from orbital dynamics or atmospheric drag. The attitude control of the system controls the orientation and directs the propulsion system to change location, using a combination of hardware and software to determine position. Attached to the structure are actuators called magnetorquers that use the Earth's magnetic field to create torque for the attitude control system to reduce tumble and maintain orbit. Combined with the magnetorquers, thrusters are attached to the structure that use a cold gas, monopropellant, and the Hall effect to ionize the propellant to redirect the satellite back to orbit, or de-orbits the satellite at the end of a mission.

Communication devices like modems take the analog signals and digital signals provided by the satellite and convert them into radio waves that can be transmitted back to ground control receivers. Transceivers, repeaters, and antennas collaboratively work on signal movements, receiving and relaying information or instructions. Telemetry information and payload data is provided to the ground control center in real-time to make sure the satellite is operating appropriately, while instructions and software/firmware updates are sent by the control center. This complex web of signals is managed on networks through internet connected ground stations that are deployed by space agencies or private commercial entities. Payload interfaces keep operators aware of payload safety status and collect the data retrieved by the payload instrument. Because of the standardization practices in the satellite industry, instruments can be developed and deployed quickly without major modification to the satellite structure. Less work applied to building new satellite designs every time an operator employs one has made the cost of satellite use affordable to more institutes (Promwad (2025)). Additionally, the communication networks provide data to ground control centers, operators are able to use the data independently of a mediating operator, personalizing the data access to the operator to make data analysis more consumable.

Thermal management has been broadly simplified, as with other embedded systems the advances and attention to development have been focused on the computational increases. The reason why the focus on thermal management and power supplies hasn't been regarded as a priority is because of effective applications that are currently in use. With no atmospheric changes and full exposure to the harsh realities of space, satellites are already heavily guarded against the elements with little room for improvement in the current standards.

Onboard computers are housed in the main bus unit, composing of on-board flight computers (OBC), attitude determination and control systems (ADCS), and redundant ultra-high frequency (UHF) communication systems (COMM). The on-board computers allow satellites to make software and firmware updates from orbit and control processes between the different components. RAM, FLASH, and fixed mobile convergence (FRAM) memory components are integrated in the on-board computers so the computers can make data collection and revisions in orbit instead of relaying the data to ground centers and potentially losing valuable data. Position computer components are also inside the main bus unit, such as gyroscopes and on-board magnetometers that the ADCS can use to send instruction to the attitude control. Similar to other embedded systems, modern satellite embedded systems can range from CAN, SPI, I2C, UART/USART, and debug interfaces like USB or the ARM microcontroller interface serial wire debug (SWD). PMW and GPIO outputs are also commonly found on satellite systems, especially when the system requires digital and analog inputs (Kongsberg (2023)).

4 Conclusions

In conclusion, satellites have become an indispensable and important aspect of industry. Satellites are categorized by the orbit they occupy that correlates to the distance from Earth' surface as well as the type of mission the satellite is performing. Construction of satellite embedded systems are faced with many challenges, such as data security, radiation exposure, power constraints, and scalability. Standard practices limit design choices but also increases the development time of satellites while informing of successful approaches to design that eliminates some challenges. Embedded systems in satellites are a complex combination of components that exploit software and hardware advantages gleaned from embedded technology advances. With an ever-increasing want for satellite missions, embedded satellite systems are expected to grow into an industry that uniquely addresses the hazards of Earth's orbit and beyond.

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