The Relevance of a Satellite Hardware System and Impact of CubeSat Mission Success

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Background of the Study

The purpose of this project was to develop a data acquisition hardware system for a CubeSat satellite project led by the Mechanical and Aerospace Engineering Department at the University of Virginia. The MAE Spacecraft Design class is currently interested in research regarding hypersonic space gliders. In order to develop a greater understanding of the elements faced by a satellite during atmospheric reentry, the class decided on developing a CubeSat satellite that will get launched into space at some date in the future and dropped as a payload. The craft will then orbit the Earth for a designated amount of time and reenter the atmosphere, ultimately burning up. To provide a high-level visual illustration, the CubeSat is approximately one foot in length and has a cubic body with side lengths of roughly six inches. On top of the body is a nose cone, which accounts for the remaining six inches in length. The electronic systems are embedded within the satellite's cubic body. During reentry, the class seeks to gather outside pressure and temperature data in order to gain greater insight into external elements during this phase of the mission. However, since the satellite will disintegrate, an electronic system is required to provide a ground station with the desired data. At a high level, sensors and electronics within the satellite will collect and send information to an on-board computer (OBC). The OBC, which is connected to an Iridium transceiver, will then transmit the data to an Iridium satellite via antenna, which will then transmit the information to a ground station located within the mechanical engineering building at the university. Two Capstone members, Luke and Connor, were assigned to configure the hardware and software involved with the Iridium Transceiver-OBC connection. I was assigned to develop the hardware that could transmit temperature and pressure data to the OBC. In order to gather temperature and pressure data, four thermocouples and four pressure transducers were placed around the body of the satellite, which were selected by the Spacecraft Design class. Each thermocouple had its own analog-to-digital (ADC) converter, which could take analog voltage signals and convert them to serial peripheral interface (SPI) data packets to be read by the OBC. It should be noted that all of the hardware for this portion is configured on a single printed circuit board (PCB). All the pressure transducers were connected to a single quad ADC, which also performed the function of digitizing analog signals into SPI data packets for transmission to the OBC. The choices of hardware: OBC, pressure transducers, thermocouples, ADC chips, were already made by the Spacecraft Design class, my only role was to create a PCB with the desired system and test functionality from both a software perspective, with my partner Yul, and from a hardware perspective.

STS Abstract

The purpose of the STS portion of this thesis is to identify the novelty and relevance of this system as it relates to prior art. Capstone projects in the electrical and computer engineering department generally revolve around both the functionality and use of a particular novel idea. In order to discern a project’s usefulness and application to society, it is helpful to identify existing related patents in order to gauge the "patentability" of the device in question. I will be considering both the data acquisition and transmission components of patents when relevant despite only working on an acquisition for the CubeSat. Using these cases and official U.S. patent requirements, I will gauge the overall patent-worthiness of the system. Afterwards, external considerations will be considered for the hardware system based on NASA/electronic standards and other external considerations. A brief discussion of the general impact of a successful CubeSat mission will complete the STS paper.

Literature Review

In discerning the relevance of hypersonic flight technology, it is helpful to examine a brief history of technological developments in the field. In 1949, a V-2 rocket became "the first object of human origin to achieve hypersonic flight," or fly faster than five times the speed of sound (Anderson, 2012). Since then, there have been many weapon and aircraft systems that have traveled at these speeds, including NASA's X-15 experimental rocket project and many of the reentry vehicles from the Apollo missions. Regardless, of the propulsion system, there are many technological challenges that must be overcome when developing hypersonic flight systems, from cost difficulties to obstacles in aerospace design and necessary improvements in combustion engineering (Van Wie, 2021). To conduct further research in the field of hypersonoics via data collection, the University of Virginia is attempting to design, build, and drop a satellite spacecraft payload. Omitting a jet propulsion system eliminates a significant source of cost, skill, and labor, allowing engineering efforts to be directed towards areas such as power management, aerospace design, and hardware development. In order to gauge the potential impact of the CubeSat, patents related to the data acquisition/transmission system must be considered alongside relevant standards, so that the novelty and relevance of the technology is understood.

Given that Capstone projects in the electrical and computer engineering department revolve around the tangible development of a specific technology, examining existing patents is relevant in gauging the patentability of the proposed device and learning about current developments in the field. In discerning the patentability of an invention, Section 101 of the U.S. Patent Act is most useful, which states: "Whoever invents or discovers any new and useful process, machine, manufacture, or composition of matter, or any new and useful improvement thereof, may obtain a patent therefore, subject to the conditions and requirements of this title." (U.S. Patent Act of 1952).

This section explicitly indicates two qualifications: utility and novelty. A third, tangibility, is implied in the indication of the object's required substance: "process, machine, manufacture..." (U.S. Patent Act of 1952). In its interpretation and application, a fourth requirement of the invention being "nonobvious," is observed ("Patent Requirements" (BitLaw), n.d.).

Both the data acquisition and transceiver CubeSat systems satisfy the "statutory" requirement that relates to the substance of the object in question ("Patent Requirements" (BitLaw), n.d.). Both are not only explicitly defined systems that have a set of requirements for operation and an expected result but are also physical systems that require the assembly of components on a PCB for implementation. Since these systems require manufacture and fabrication for physical use, the third requirement of Section 101 is satisfied by the object of this Capstone project. Literature and music are two cited examples that fail to satisfy this requirement and one can easily see how the CubeSat electronic systems differ significantly in essence from these works ("Patent Requirements" (BitLaw), n.d.). The "tangibility" requirement for patentability is also satisfied by the data acquisition/transmission PCBs.

The first requirement of Section 101 in the U.S. Patent Act of 1952 requires that the invention be useful. While this is subject to interpretation, the object simply needs a purpose, regardless of gravity. The purpose of the CubeSat data acquisition system is to convert analog thermocouple and pressure transducer data into digital SPI signals, which can be interpreted by the satellite's on-board computer. The transceiver system is designed to communicate the aforementioned and all other data to an Iridium satellite via antenna, which is then received at a ground station. This succinct purpose means that this capstone project satisfies the usefulness patentability requirement.

In order to discern novelty, one must consider relevant prior art. One patent that is similar to the CubeSat's data acquisition and transmission circuitry is the patent entitled, "Aircraft flight data management data system and corresponding method," which illustrates an "on-board data acquisition, storage and transmission system" (Kolb et al., 2011). At a high level, the on-board computer system contains a "data acquisition module," which handles various sensor inputs and communicates them through an interface to a microcontroller within the "storage and control module," which manages data storage and memory through an FPGA. Data at the interface is also communicated to the "communications module," where it is transmitted to a satellite and then to a ground station through a gateway. Additionally, the invention can transmit data to a user via email (Kolb et al., 2011). Although the overall goal of this patent is similar to that of this Capstone, the application is different, likely affecting the system architecture, and it is much more complex. The communication module in the patent is similar to the Iridium transceiver PCB, although it contains a "satellite modem," "RS 222 interface," and an "optical isolation component," which is beyond the scope of this project (Kolb et al., 2011). The OBC can be likened to the storage control module, although hardware breakdown of the computer itself is not relevant to the Capstone. Finally, the pressure transducer and thermocouple ADC chips perform part of the task allocated to the data acquisition module in receiving sensor signals but differ in using SPI to communicate with the OBC. These discrepancies between the invention outlined in the selected patent and the capstone project show that while the CubeSat electronics are not necessarily more complex, they describe a fundamentally different system, indicating novelty.

In the patent, "Self-Contained Flight Data Recorder With Wireless Data Retrieval," de Leon and Quiros present a design for an on-board device that captures and stores flight data, such as "G forces, flap position, cockpit voice and others," and transmits them to a computer via RF transceiver. In the sensor architecture, the raw temperature signal must first pass through a differential amplifier and the air pressure signal must first pass through a "noise de-coupling filter" before reaching the microcontroller. While the overall concept of recording flight data and transmitting it to a ground station is the same as that of the CubeSat, the application and implementation of the electronic systems differ. The patent's design is meant for "small aircraft" while that of capstone is meant for satellite applications (Leon and Quiros, 2005). As an example for how discrepancies may manifest, the CubeSat PCB must contain radiation-tolerant components, heat dissipation methods, and increased stability measures, while PCBs meant for aircraft likely do not need to account for these constraints. Additionally, rather than using a differential amplifier and noise de-coupling filter for temperature and pressure signals, respectively, the raw sensor signals are directed into MAX11254 and MAX6675 ADC chips directly for processing by the OBC via SPI. Perhaps the biggest difference is that rather than using a complex microcontroller architecture for data processing, the CubeSat simply uses the designated OBC with all necessary functionality built-in. Similar to the previous two selected patents, in "System, Methodology, and Process for Wireless Transmission of Sensor Data Onboard an Aircraft to a Portable Electronic Device," Warner and Rucker present a data "monitoring and reporting" system for aircraft applications. In the enclosed system, a data recorder intakes and processes data from external sources and transmits it to an electronic flight bag or receiver device via wi-fi network. There are also system architectures for how the data transfer can remain encrypted and displayed (Warner and Rucker, 2017). Aside from the specific data acquisition components, the CubeSat system differs from the described invention in that the PCB-mounted Iridium transceiver is meant to communicate data from the OBC to a satellite and eventually to a ground station via RF transmission, rather than through a local encrypted wi-fi network. Through a reasonable patent search, the differences found between the CubeSat electronics and the aforementioned patents indicate a degree of novelty, satisfying the final requirement for patentability and indicating that the developed data acquisition and transmission systems could be patented with confidence that the project is novel, tangible, and useful [1].

External Considerations

When considering hypersonic space flight development, it is important to understand relevant standards that ensure on-board systems are suitable for space flight along with general considerations for physical resilience. Compliance with these standards and considerations is also necessary for any societal impacts the system might have. There are four primary external considerations relevant to this project in the development of space-grade electronics: cleanliness, volume, radiation/temperature tolerance, and vibration tolerance. Each of these will be discussed in further detail and in relation to the compliance of standards that address each issue. These considerations were not necessarily implemented in the Capstone project itself due to time constraints and the remainder of the work that had to be completed on the CubeSat by other groups. Essentially, it was too early in the design process to adhere to particular standards, as functionality was the greater priority. These considerations, however, were included in the final Capstone report.

Given the amount of time for which the satellite electronics must be operational and the cost of the entire project, it is imperative that each PCB remains clean during fabrication and implementation. Chemical residue could affect the performance of mounted components and conductivity of traces, potentially skewing device communications and the data transmitted from the satellite. To mitigate the impact of unclean electronics, NASA standard NASA-STD-8739-6A

[1] The majority of the "Literature Review" section of this paper was taken from my Capstone project's final report. I was the author of this section, but it deserves a footnote, as it was still taken from another source. The report is unpublished and its title is "Capstone Final Project Report". I received permission from both my STS and technical advisors to reuse this portion of work. This section was re-framed from a strictly patent-ability context to a technological relevance context.

outlines approved methods of cleaning PCBs (NASA-STD 8739.6A, 2016). Deionized water, isopropyl alcohol, and ultrasonic cleaning are all approved substances or methods for cleaning PCBs. The first two chemicals are easy to obtain, while an ultrasonic cleaning device is much more difficult to obtain and costly. When addressing each issue, the group must ultimately exercise prudence over the degree of adherence to a particular standard. Certain approved practices are simply too costly, time-consuming, or unreasonable for the scope of the project. After wet cleaning, standard NASA-STD8739-6A indicates that de-moisturizing must be executed by placing the cleaned component in an oven for at least four hours at approximately 194 degrees Fahrenheit. The presence of fluid will drastically impact the performance of electronics, so this section of the standard must be strictly adhered to. The standard also mentions how time must be dedicated to preventing adhesives and materials that could cause residue from contacting the PCB. From NASA-STD-8739-6A, the group produced a process for ensuring PCB cleanliness. First, all residue must be removed from the blank PCB using either deionized water or isopropyl alcohol. Then the PCB must be de-moisturized by placing it in an oven for four hours at 194 degrees Fahrenheit. Throughout the soldering and component-mounting process, careful attention must be dedicated to avoiding contaminants and removing leftover substances from the PCB surface. Tools such as anti-static brushes will help in maintaining continual cleanliness. The second external factor that must be considered is the combined volume of the electronics. As a crude approximation, the cube that houses the electronics has a side length of six inches. Some of that space is already used by the on-board computer, meaning that the PCBs must be designed to fit in a confined space. This means that components must be mounted as closely as possible without positioning conflicts and convoluted trace/wire routing. Additionally, the PCB components will most likely receive sensor readings via board-mounted wiring connectors. These connectors cannot take the form of standard PCB jumpers, as the height required to make these connections would limit the amount of available space. A potential solution to this problem is mounting wire connectors to the top or bottom of the PCB facing parallel to the board's surface. Connecting sensors at the sides of the PCB will reduce height and yield a more compact design. Depending on the availability of space, the circuit designs produced by the two sub-groups might have to be combined into a single, larger PCB.

The third external consideration is radiation/temperature-related stressors on the electronics. Heat concentrations experienced by the PCB can overheat circuit components and drastically reduce device performance. Therefore, heat dissipation methods must be employed to account for the extreme temperature conditions of outer space and the Earth's atmosphere. Firstly, all PCBs must be fabricated out of heavy copper, as they support "elevated current through the board and assist in transferring the heat to an outer heat sink for more efficient heat dissipation" (PCB International). The use of heavy copper PCB material provides for a rugged design that is more tolerant to the temperature-related pressure of the mission's environment. Regarding circuit design, thermal vias must be placed under specific components that are prone to overheating, such as the thermocouple amplifier and the pressure transducer ADC quad chips. Thermal paste is susceptible to outgassing, which is when a lack of pressure in the vacuum of space causes bubbles to form in the chemical's surface. This potentially impacts device performance and creates residue around the PCB and interior of the satellite.

The fourth external consideration that must be accounted for in the electrical design is the elements of outer space creating a high load/vibration environment. During atmospheric reentry and potentially during the initial launching stages, the satellite will be exposed to a considerable amount of force and vibration. The electrical systems must be designed such that these forces do not affect device functionality or the structural integrity of components. NASA standard NASA-STD-8739-6A recommends the use of staking before the mounting of PCB components. This involves staking paste being applied to the sides of mounted components to hold them in place and make them more resistant to shock and vibration. Staking paste is cheap and easy to use and the NASA standard dictates how it can be best applied to circuit components of different shapes. In addition to device mounting, the PCBs themselves will most likely be mounted with screws to ensure stability. NASASTD-8739-6A recommends the use of thread-locking methods to ensure that screws are tightly bound and mitigate the impact of extraneous forces. Finally, the standard indicates the necessity of using conformal coating during the final stages of PCB development. Conformal coating can be applied to a PCB via a brush to increase resistance to foreign elements and bolster structural integrity. The coating should first be applied to a dummy PCB to discern the appropriate thickness of the coat before being applied to the actual board. From NASA-STD-8739-6A three steps should be taken to ensure the PCB resilience to vibration: staking after part mounting and testing, thread locking, and conformal coating during the final stages of development.

There are some general considerations outside of the four main external factors that must be accounted for when designing electronics for space travel. NASA adheres to IPC standard J-STD-001FS, which mandates the use of lead-free tin solder (Electronic Assemblies J-STD-001 Addendum Task Group, 2015). The reason for this decision was surprisingly not explicitly stated in the standard, although it is most likely due to the health concerns surrounding lead or potential material residue that could affect circuit functionality. Standard IPC-A-610, which indicates measures for quality electronic assembly, recommends that all components, when mounted to a PCB, are meticulously inspected for damage and insecurity and that all soldering joints are perfectly formed (IPC-A-610: The Standard for Acceptability of Electronic Assemblies, n.d.). The standard also recommends marking each component to improve organization and traceability. There will not be an excessive number of components on the group's PCB boards, but adhering to this standard would still be good practice. [2]

Conclusion

From the STS portion of this paper, the patent-ability for this device was first discerned by considering prior art. By examining patents for data acquisition and transmission hardware systems of similar applications, one can see that a patent could be potentially filed for the CubeSat electronics DAQ system. At the present, there are few (if any) existing patents for propulsion-less hypersonic flight systems. This indicates the potential for the development of standards and innovations for this field, provided that the CubeSat system is operational and functions as expected throughout the mission. In my mind, it is not the data gathered by this project that will produce a groundbreaking result, but the mission itself. Proving that a university group with a relatively small budget is able to gather any hypersonic data at all means that the barrier to entry of this field can be lowered, as current hypersonic testing environments are limited and costly ("HyCUBE Overview", n.d.). Proper functionality will indicate great success and potentially pave the way for continual small-scale hypersonic flight technology development, both for the University of Virginia and other institutions. By gauging the patentability of a small-scale project such as this one, we can see that there are larger implications for hypersonic space flight developments that do not require the use of propulsion systems. For these developments to be

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realized, however, external considerations for this project must be examined and adhered to. The specific standards examined here were NASA/electronic standards and other general considerations related to the elements of space. In the technical portion of the thesis, we will consider a more in-depth view of the electronic system and general results of design and experimentation.