Application of Embedded Systems in Low Earth Orbit for Measurement of Ionospheric Anomalies

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***Abstract*: Space is a hazardous environment for both man and machine and to explore such a terrain a rugged, yet easily implementable, platform is needed. Low-cost, low-power embedded systems are the ideal solution since they allow for parallel development of components, which results in quick turnaround from inception to design. We present a design for detection of ionospheric phenomenon in Low Earth Orbit using embedded systems on small scale satellites. We describe the operation and architecture of this design.**[1]

Keywords: embedded systems, satellite, ionosphere, signal distortion, low earth orbit, cubesat, picosatellite, faraday rotation, space

I. INTRODUCTION AND BACKGROUND

One the earliest forms of modern embedded systems was the Apollo Guidance Computer (ACG) developed by MIT Instrumentations Laboratories. The ACG was used for calculating, relaying, and controlling all flight information on the Apollo manned satellite missions [1]. This guidance computer was one the first systems to use the new monolithic integrated circuits (ICs) that had just came on the market. Now man is returning to space for more complex missions, but the strategy has remained the same: to use embedded applications to develop space capable vehicles for research and exploration.

Performing research in space is a costly endeavor if it is performed by a human. Special care must be taken to safely transport, maintain, and retrieve the human researcher. But if the test can be performed remotely or even autonomously, then the human element can be replaced by an automated embedded system. One such type of test that interests scientist are those performed on the charged particles surrounding earth in the Ionosphere. This region of space acts as the boundary between the cosmic dynamics of the universe and the edge of our atmosphere.

The Ionosphere resides approximately 50-1000km above the surface of the earth and is very well known for influencing radio wave propagation on earth. The Ionosphere is produced by the ionization of atmospheric neutrals by ultraviolet radiation from the Sun. The Sun is also spewing out charged particles, the so-called solar wind. The charged particles from the Sun, impinging on Earth become trapped by the magnetic field lines and spiral along the lines down to the poles, creating such well-known effects as Auroras. In Low Earth Orbit (LEO), where many earth orbiting satellites reside, these cosmic energies can be observed as they smash into our atmosphere [2].

The need for an unmanned, autonomous platform for basic science research in the Ionosphere led to the development of a satellite designed to measure the Faraday rotation, induced by the Ionosphere, on the polarization of electromagnetic waves generated by the satellite and correlate this phenomenon with solar variability. The Faraday rotation refers to the rotation of the plane of polarization of electromagnetic waves propagating in a plasma embedded in a magnetic field. The satellite, known as the AubieSat-1, was developed by the Auburn University Student Satellite Program, founded and directed by Dr. J-M Wersinger. By noting the rotation of the plane of polarization of the electromagnetic waves sent by the satellite, we will be able to predict how solar loading will influence the density of the Ionosphere that affects communication between terrestrial stations and satellites, and the

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survivability of satellites. The remainder of this paper is organized as follows: Section II will discuss the science mission. An overview of the satellite subsystems is given in Section III. Hazards of space environments are discussed in Section IV. Data collection and transmission is covered in Sections V through VII. The remainder of this paper discusses the current design stage of the satellite.

II. SCIENCE MISSION

The Ionosphere can be broken into multiple layers, as depicted in Figure 1. The first and closest layer to earth is called the D layer, starting at approximately 50km from the surface of earth. This distance depends on the solar activity [2]. If ionization can be thought of as a removal of electrons from an atom, then recombination is the opposite effect where the newly freed electrons attach to electrically unstable atoms. Within the Ionosphere there is a constant struggle between ionization and recombination that determines the characteristics between each layer. Within the D layer, there are not many free particles due to the density of our atmosphere at this level. This leads to an increase in recombination of the particle that have been ionized. As an effect, high frequency (HF) radio transmissions are not reflected by this layer. The next layer is the E layer, beginning at approximately 90km above the surface of the earth. This layer is affected by more radiation than the D layer, allowing for higher ionization and higher density of ions and electrons. The E layer normally reflects only low frequency transmissions, but under periods of high radiation from the Sun, it can reflect HF signals [2]. The final layer is called the F layer and begins at 160km. This layer is the most exposed to solar and cosmic radiation. During the daytime, the layer becomes so inundated with radiation that it splits into two regions F1 and F2. The F layer is the most responsible for the cutting off of lower frequencies radio waves and the propagation of HF radio waves [2]. Because the satellite will be travelling at 700km above the earth, it will be well above these layers, allowing the satellite to transmit directly through all three layers.

Ionospheric conditions are usually measured at a single point, using a single sensor or array of sensors on a spacecraft in the Ionosphere. This sensor may be as simple as a magnetic sensitive resistor or as complicated as a particle energy telescope encased in 1 inch thick lead. The distance between multiple simultaneous measurement readings arei limited to the size of the satellite. In launching a spacecraft, volume and weight are expensive attributes to consider, so a limited area of sensor real estate is available. This creates a need for expanding the range of the sensor array without increasing the size of the satellite. To achieve this, we utilize the transmitter as a science instrument. By using a high enough frequency to be above the plasma frequency cut-off in all regions, our EM waves propagate without reflection but the plane of polarization of the waves rotates. The rotation is proportional to the density of charged particles. Thus by measuring signal rotation, we can measure the density of charged particles.

In the 430 MHz range of frequencies used by our satellite, the ionospheric plasma allows three types of waves to propagate: the Extraordinary wave that propagates across magnetic field lines and two waves that propagate along the field lines, the right – R - polarized wave and the left – L - polarized wave. The R-wave and the L-wave propagate at different speeds. The difference between these speeds is proportional to the ionospheric plasma density. This effect produces a rotation of the plane of polarization. Thus measuring this rotation, called Faraday rotation, yields the ionospheric plasma density. By comparing the original polarization of the wave at the satellite with the wave observed on the ground, the average ionospheric plasma density along the wave path is obtained. This is illustrated in Figure 1.

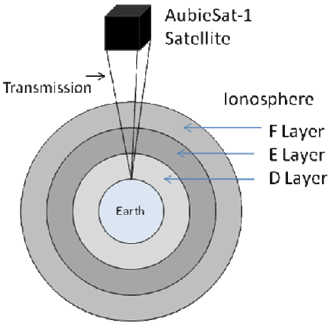

Figure 1: Satellite transmissions as it travels through the ionospheric layers.

III. SATELLITE SYSTEM OVERVIEW

The satellite is designed and fabricated for use in LEO. The size is 10x10x10cm and has a mass just under 1 kilogram. Due to the small size and shape of this satellite, it is classified as a picosatellite (or cubesat) [3]. This satellite can be easily thought of as a combination of distinct parts: Command and Data

Handling (C&DH), Electrical Power Systems (EPS), Communications, and Payload Sensors. At the core of the satellite, as with most modern embedded systems, is a microprocessor. The microprocessor controls the power regulation systems, collection of real-time data for the science mission and transmission status of the communication systems through a real time operating system (RTOS). The interconnections between these components are illustrated in Figure 2. The ATMEGA 128L microcontroller from Atmel was selected due to its low power requirements and large integrated Flash program memory [4].

As the satellite travels through space, power is generated by solar cells that collect solar radiation from the Sun and any albedo reflected from earth. On earth, the ground is the point of reference for observations, but in space the largest object is the Sun. Solar orientation is determined by using current sensors connected to the solar cells that power the satellite to create a course Sun sensor. Using current measurements, the embedded processor can determine mathematically its orientation relative to the Sun. By performing simple cosine calculations, one can determine the angle of each side of the satellite in reference to the Sun. If the Sun's rays are perpendicular to the surface then the incident angle becomes zero and the maximum collectible power is observed on the solar cells. Inversely if the cells are parallel to the Sun's rays, then no solar energy will be collected [5]. The results of this cosine calculation appear in Equation 1, where P_d represents the collected power, Θ represents the incident angle between the normal vector of the surface and the direction of the Sun, and P_o represents the maximum collected power. The results of this calculation, along with other health statistics, can then be sent by the transmitter so any observer with a receiver can pick it up.

$$P_d = P_o * \cos(\Theta) \qquad (1)$$

The communication system acts as both a data relay point between the satellite and a ground observer and the science mission. The communication system comprises two frequency shift keying (FSK) channels. In an FSK transmission scheme logic low and logic high are represented by different discrete output frequencies separated by a set difference. The required frequency difference is determined by the noise figure and bandwidth of the encapsulated signal. The first channel is called the primary transceiver system as it is a bidirectional channel for transmitting data to and from the satellite. It is also responsible for producing a tone during the science mission to be observed by a ground station observer with two orthogonally oriented dipole antennas. This tone will become warped as it passes through the Ionosphere. This communication channel is controlled by a terminal node controller (TNC), so that received and transmitted signals can be distinguished from one another. The second channel is a single direction channel comprising of only a receiver. This channel is used to communicate an emergency shutdown command in the event that a failure occurs in the primary system.

To generate an FSK transmission, the Melexis TH72011 FSK Transmitter was selected. This transmitter can generate a +10dBm signal in the range from 380 to 450 MHz [6]. To receive this generated signal, the Melexis TH71102 FSK receiver was selected, as the two ICs are a matched pair [7].

The operating output and input sensitivities of these ICs are not powerful enough to travel the 700km distance from the upper Ionosphere to the ground and still be detectable. Therefore, an amplifier is required to detect and transmit the signal. To amplify the transmission coming from the satellite, a switching transistor amplifier was designed using the NPN Silicon Germanium RF Transistor NESG260234 by NEC [8]. This increases the maximum output of the Melexis transmitter from +10dBm to +30dBm. For the receiver, a low noise amplifier was implemented using a similar principle with an N-channel dual gate MOSFET to create a low noise amplifier to increase the sensitivity by +20dB [9].

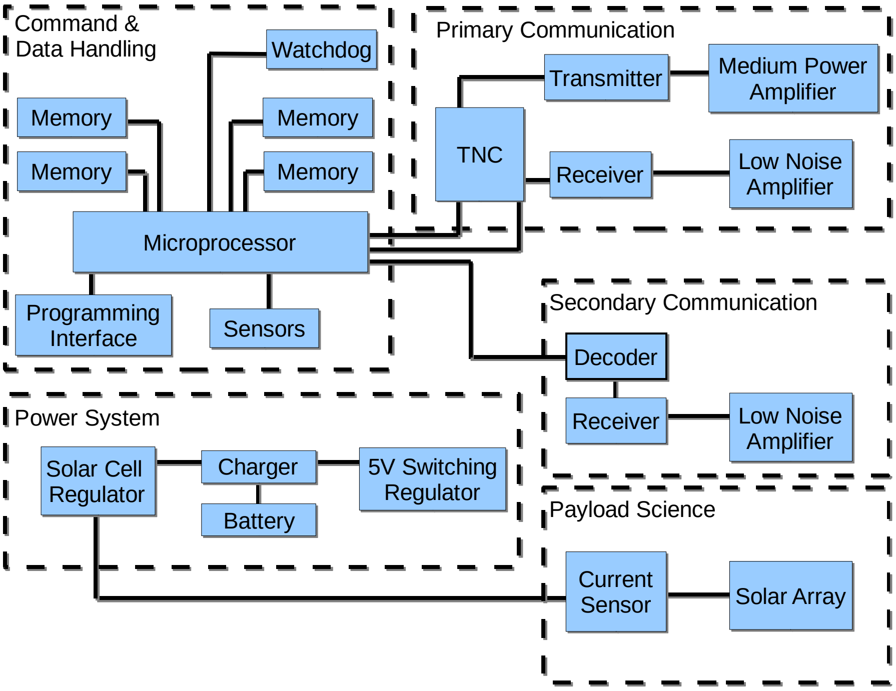

Figure 2: Block diagram representation of internal components

Power on the satellite is harnessed from the Sun using photovoltaic cells attached to the exterior of the satellite. These are the same solar cells that the microcontroller uses to detect the position of the satellite relative to the Sun. The power from these solar cells is routed to the satellite through a switching regulator to convert the voltage of the solar cells to the voltage within the operating range of the other components on the satellite. Any excess power generated can be routed to Lithium-Ion batteries to be stored and used when the satellite is in a part of the orbit that has the earth between it and the Sun. An illustration of this internal configuration of the satellite can be seen in Figure 2.

IV. EMBEDDED SYSTEMS IN THE SPACE ENVIRONMENT

Space is a very inhospitable environment for embedded computing systems. High energy radiation, high speed particles and extremely high and low temperatures are among daily concerns. It is these factors that excite the Ionosphere, causing the warping of radio transmissions that we are interested in. However, to measure these events, a science satellite must be able to survive in them. To combat this, a thin anodized aluminum shell is used to construct the frame of the satellite and to shield its components from some of radiation and space debris. ICs that contain components that are susceptible to damage from magnetized particles can be protected with high permeability metal shields [10].

Another critical concern in space applications is the susceptibility of program code to a single event upset (SEU) caused by radiation. An SEU can take the form of a simple bit flip in the program code or as an ion implant that results in a latch up of the power rail to ground. Though not all SEUs are preventable, most are repairable. To protect the program code from being changed by radiation, the microprocessor contains three copies of the program. Each version is tabulated through a checksum calculator. If the checksum of any one version does not match, it is replaced by the version that does not have checksum errors. This allows the program to continue to run long after errors in the code have been detected. This error check is run periodically to verify that the program code is intact.

If a software error is not caught, it is possible for the program to become so corrupt that the microcontroller will stop responding to the external watchdog controller. This will force the watchdog to restart the microcontroller. If the microcontroller was stuck in a loop or a code error wasn't detected, this will give the microcontroller the chance to perform those checks by power cycling the IC.

One major advantage to sending a human to perform a task is that, once complete, they can perform additional tasks. Embedded systems can perform a limited range of tasks, but once implemented they can be reprogrammed many times to perform different tasks. It is with this in mind that this system is capable of being reprogrammed after deployment in space and the original primary mission has been completed [1].

To protect against losing critical information in the event that power is lost during operation, important system variables are recorded in external flash memory when changed. Once power is restored, the variables can be recovered from the external memory. In addition to this method, most of these key variables can be written from the ground station to the satellite over the communications channel.

V. DATA COLLECTION AND PROCESSING

The science mission starts when the ground stations transmits, to the satellite, commands that allow the satellite to begin transmitting the science mission signal. At this time, the satellite configures itself to perform the science mission and begins transmitting the science mission transmission for detection by the ground station.

To determine the position and orientation of the satellite, a combination of solar cell data and Keplerian elements are used. The Keplerian elements will help determine the location in the sky as they contain orbital path information. The solar cell data contains the amount of power each face of the satellite generates. This is proportional to the cosine of the incident angle between that side and the Sun. This data is sampled and stored in short intervals. The shorter the intervals, the higher the rotational resolution will be. This correlates to a larger required memory. The purpose of knowing the orientation of the satellite during transmission is that the satellite's orientation is equivalent to the satellite's transmitting antenna's orientation. Knowing this information is essential for knowing the received signal pattern.

Figures 3 and 4 show the best and worst case for signal strength. Figure 3 shows that the dipole antenna on the satellite and the antenna on the ground are ideally aligned. But as the satellite tumbles in space, it may be that one of the antennas is not pointed in the correct direction. This is illustrated by Figure 4, where it can be seen that receiving antenna does not point in the correct angle to detect the satellite’s transmission. This will result in little to none of the transmitted signal being received by the antennas.

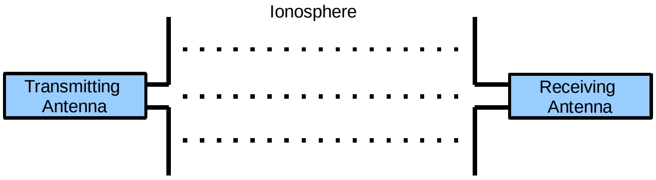

Figure 3: Perfect alignment of dipole antennas

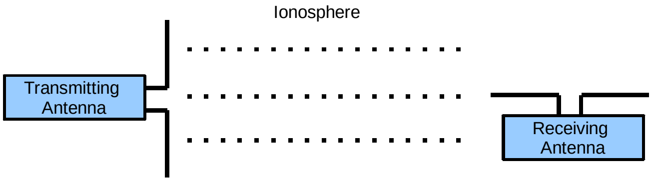

Figure 4: Orthogonal alignment of dipole antennas

The data collected during the science mission is stored by the microcontroller in external flash memory for transmission to the ground station after the science mission is complete. Once the data has been transmitted to the ground station, it is removed from the flash memory, so that more science data can be stored for the next mission.

VI. INTRA-SATELLITE COMMUNICATION:

The satellite comprises many components on separate printed circuit boards (PCBs). All of these components need to relay data back to the Command and Data Handling microprocessor. This is achieved using two types of data paths. The first is a digital logic line stretched between an input or output pin at the far end device and the microprocessor. The second type is an inter-integrated circuit (I^2C) communication channel. This communication channel allows for the use of commercial devices that can communicate over I^2C

to be used for processes like analog to digital converters or expanding the digital input/output bus.

VII. GROUND COMMUNICATION PROTOCOL:

Occasionally there is a need to communicate between the ground station and the satellite. To achieve this we utilize one piece of hardware and two packet formats. Between the primary communication system and the microcontroller, there is a terminal node controller (TNC). This TNC has many functions. The first is to control the state of the communication system to be in either transmit or receive mode. The second is to communicate between the microcontroller and itself in a format know as KISS (keep it simple, stupid) over the Universal Serial Asynchronous Receiver Transmitter (USART) port. This simple protocol allows the microcontroller to encode another packet format type known as AX.25 within the KISS packets. When this combined packet is received by the TNC, the TNC will remove the KISS formatting leaving only the AX.25, as illustrated in Figure 5.

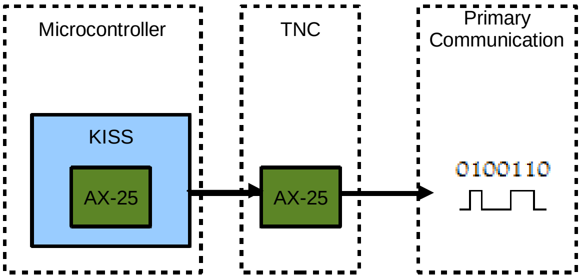

Figure 5: Encapsulation of packetized data

AX.25 is a popular amateur radio data-link layer communications protocol that allows for packetized data. It is a modification of the X-25 protocol for wireless transmissions [11]. Contained within this protocol is the ability to label packets, identify the sender, and send both connected and unconnected packets. This allows for the link between the ground station and the satellite to establish a strong and secure connection. In the event that a packet of data is lost during the transmission or has an incorrect checksum, it can be recovered simply by asking for a retransmit of that one packet.

VIII. PROTOTYPE'S STATUS:

The current prototype, consisting of each individual subsystem, has been constructed separately on FR4 type PCB boards. Each subsystem has been built and is undergoing testing.

The command and data handling system has been able to program the ATMEGA microcontroller to include a custom made file system to store collected data with timestamp information, interface to a real time clock, multiple external 32MB flash memory ICs, external ADC and GPIO expanders on the I^2C bus. The hardware and software aspects of this microprocessor design have begun an integration process to guarantee that all external devices will properly interface to the software aspect. The communication interface to and from the TNC has been completed and is undergoing testing.

The communication system has successfully transmitted and received data and has been able to decode this data. Current testing and calibration is ongoing to improve performance and reduce internal loss. The TNC is still undergoing development.

The EPS system is able to convert and store power from a low power array of solar cells to a battery. EPS has also been able to pull up to 2 amperes of continuous current from the system and still remain safely within operating conditions.

IX. FUTURE DEVELOPMENT:

The first completed prototype of the satellite is expected to be completed by the end of summer 2009 for demonstration and exhibition. Once a working model is completed, a launch date and vehicle can be coordinated at that time. There are many organizations that coordinate the launch of small unmanned space probes. One such organization is the California Polytechnic State University CubeSat Program [3]. In addition to these organizations NASA has just recently announced a program to launch stand-alone satellites into orbit [12].

Once this satellite is launched, the expected mission length is only 3-6 months, but it will remain in orbit and continue to perform the mission until it is decommissioned or drops out of orbit and falls back to earth. When not actively performing the science mission, this satellite will be able to respond to amateur radio operators who wish to communicate with it. When it is launched, Keplerian elements provided by the North American

Aerospace Defense Command (NORAD), uplink and downlink transmission frequencies, and transmission procedures will become available to the public at the AubieSat website [13].

X. CONCLUSION:

The Ionosphere is just out of reach for scientists to run simple continuous tests. Any device launched into space will eventually de-orbit and burn as it falls back to earth. So a test platform needs to be used that is cheap to construct and easy to develop. An embedded system is the ideal choice for this platform.

An embedded system is ideal because in space it can be designed to perform certain missions and return the results of that mission to an earth bound observer. An intelligent system can also be designed so that it is reprogrammable, so that if another mission in the future is needed using the same equipment, simply reprogramming the satellite will result in a new mission. This will reduce the cost of redeveloping, constructing, and launching. Space is a dangerous place as any equipment is not protected by the atmosphere of earth, so development must be concerned with environmental impacts. The initial working prototype of this satellite is under construction and is expected to be complete by the end of this year.

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