Design Challenges and Methodology for Developing New Integrated Circuits for the Robotics Exploration of the Solar System

Mohammad M Mojarradi,
Jet Propulsion Laboratory, California Institute of Technology
Pasadena, CA 91109 USA
818-354-0997 (tel), 818-393-4272 (fax)
Mohammad.M.Mojarradi@JPL.NASA.GOV

Elizabeth Kolawa
Jet Propulsion Laboratory, California Institute of Technology
Pasadena, CA 91109 USA
818-393-2593 (tel), 818-393-4272 (fax)
Elizabeth.Kolawa@JPL.NASA.GOV

Benjamin J. Blalock,
ECE Dept., University of Tennessee, 1508 Middle Way Drive
Knoxville, TN 37996 USA
865-974-0927 (tel), 865-974-5483 (fax)
bblalock@ece.utk.edu

R Wayne Johnson,
LEAP, Auburn University, Auburn, AL 36849-5201
334-844-1880 (tel), 334-844-1898 (fax)
johnson@eng.auburn.edu

Abstract

Next generation space-based robotics systems will be constructed using distributed architectures where *electronics capable of working in the extreme environments* of the planets of the solar system are integrated with the sensors and actuators in plug-and-play modules and are connected through common multiple redundant data and power buses. Challenges for development of integrated circuits for these robotic systems deal with the reliable operation of these systems under extreme planetary environments. These challenges are compounded by a complementary set of packaging and assembly issues that address the reliability of the system from the mechanical point of view. Without exception integrated electronics developed for space systems will have to use existing commercial device and VLSI manufacturing technologies. Because of the sever difference between the extreme environment of the solar system planets and earth, IC designers of space systems have to examine the performance of all the devices in the extreme environment conditions and define a new set of design rules and models that predicts the performance and life cycle of these technologies.

Introduction and Overview of the Environments

During the next 20 years, NASA is challenged to develop the necessary technologies to support missions to extremely diverse environments. In one extreme, Venus Surface Exploration as well as Venus Sample Return missions both requires surface operation including sample acquisition from 15-20 cm depth of hard rock and in situ sensing (temperature, pressure etc.). In order to acquire samples, a Venus lander has to survive for at least an hour at about 486ºC and 90-bar pressure. Survivability in extreme high temperatures (380ºC) and high pressure (90 Bar) are also required for deep atmospheric multi-probes to Giant planets. On the other extreme, Comet Nucleus Sample Return (CNSR) missions, Titan In-Situ missions, as well as missions to Europa have to survive in extremely cold environments in the -140ºC to -180 ºC range. Missions to moon and Mars will see temperature swings of -180ºC to 110ºC. In addition, the Europa mission presents a challenge of surviving in both extremely cold temperatures (-160ºC) and high radiation (5 Mrad).

System Level Architectural Trends

Currently, electronic systems that can directly operate within the wide temperature range of solar system planets do not exist. Robotics systems such as Mars Exploration Rovers (MER) employ a “Warm Electronics Box (WEB)” to shield their electronic subsystems from the temperature changes of the environment. Unfortunately, WEB-based electronics require point-to-point wiring harnesses and a complex mesh of interconnects (1800 wires for MER) between the WEB and unshielded loads (motors, actuators and sensors). Alternatively, next generation robotic systems will be deploying wide temperature “plug-and-play” modules consisting of electronics integrated with motors and sensor [1]. These modules will be located at the extremities of the robotics system and will be connected through a distributed architecture with standard communication bus interface. Modular systems with distributed architecture are expandable and will eliminate the need for complex, heavy and difficult to integrate wiring harnesses (90% saving in interconnect wiring compared to wires in the MER). In its place, multiple redundant serial, data and power buses will be used to significantly simplify interconnects and cablings for sensors, motors and actuators. Additional benefits of these new modular systems will include 1) ease of rework and reduction of downtime, 2) reduction in the size of the WEB, along with the associated mass and power requirements of the entire system, and 3) enhanced system reliability and robustness by simple inclusion of redundant sensors and actuators.

Mission Categories and Design Impacts

In general missions to the solar system can be divided into the four categories listed below. However, the environment of every mission determines the complexity of its architecture and the technology choices for its electronics.

1) Missions to High Temperature Environments (Venus at 486ºC and Giant Planet at 380ºC): Robotic systems designed for these high temperature environments heavily rely on electronic modules that are still located in a centrally cooled electronic box inside a pressure vessel. The budget for mass and power of their systems are usually very limited and the use of central cooling devices severely drains these budgets. However, emergence of certain new commercial electronic technologies such as SOICMOS capable of operating to 250ºC [2] and SiC capable of operating to 500ºC promises to significantly benefit these robotic systems. This is because deploying traditional electronics necessitates the use of thermal control for keeping the electronics at temperatures below 70ºC. In comparison, limiting the temperature of the electronics below 250ºC significantly reduces the mass and power of the cooling devices providing a much larger portion of the overall power and mass budget for instruments and science payload. New SiC and high temperature vacuum electronic technologies are also enabling the development of high temperature sensor and actuator modules that can be distributed at the extremities of these robotic systems.

2**) Missions to Environments with Constant Low Temperatures** (-140ºC to -180ºC for Titan, CNSR): Operation at extremely low temperatures is required for Titan in-situ, CNSR as well as for Europa exploration. Both Titan in-situ and CNSR require extensive surface operation with a variety of instruments and sensors. In general, the operation of silicon devices is possible in the -140ºC to -180ºC temperature ranges. In many cases the performance of the electronics and sensors is improved at low temperatures. However many effects of operation at low temperature, especially the impact of prolonged operation of devices at low temperatures, are not well understood and need to be experimentally characterized on a case-by-case basis for every technology.

3) High Radiation Environment (Europa): Europa exploration missions require electronics that are capable of surviving in extremely high radiation levels (5Mrad in 2 weeks under 100 mils of Al shielding). NASA's X2000 program developed a radiation hard avionics system for the Europa orbiter mission. The IC's for this system are fabricated on an exclusive radiation hardened CMOS technology. Future missions of this type will have to consider the technology obsolescence issues at the time of mission definition as well as further miniaturization of the system. The emergence of radiation hardened by design techniques for development of new integrated circuits can eliminate the dependence of these types of missions to exclusive radiation hard CMOS technologies and potentially make available a larger number of technology choices for these missions.

4) Missions to Environments with Wide Temperature Cycles (Mars and Moon)

Mars surface temperature changes from -120ºC at night to 20ºC during the day. For Moon, this temperature change is between -180ºC and 110ºC. The rapid change of temperature in these environments introduces additional reliability factors that are due to mechanical stress and fatigue of the IC package [3]. These factors limit the choices for the packaging technology for the electronics. At the same time, while Si transistors operate across this wide temperature range, there are significant circuit design challenges that need to be addressed for making circuits that can operate reliably over such a broad temperature range.

Circuit Design Approach and Methodology

Prudent design practices mandate the use of commercial-off-the-shelf components (COTS) for robotic systems whenever possible. Fortunately many (COTS) are designed with sufficient margin to operate beyond their catalog specified temperature range. In particular functionality of certain digital gate arrays, analog-to-digital converters and mixed-signal circuits [1] have been demonstrated down to -160ºC. Future robotics systems for very low temperature environments will heavily utilize these components. However, for functions where COTS are not available or fail to deliver the desired performance, all space based robotic systems must use custom designed mixed signal ASICs.

Cold Temperature (-180C) ASICs: Cold temperature ASICs can be fabricated with several technologies such as CMOS, SOI CMOS and SiGe BiCMOS. However, lack of proper models (commercial technologies are only modeled to -55ºC) for performance simulation at very cold temperatures handicaps the development of mixed-signal ASICs in all of these technologies. Also, at very cold temperatures, scaling of CMOS technologies aggravates the degradation of the CMOS transistors due to hot carrier injection. Hence, optimal circuit design methodology for these temperatures is only possible though empirical evaluation of transistors at the extreme cold temperature and development of accurate models and optimal design rules.

High Temperature (250ºC and above) ASICs: For missions to high temperature environments, power is a key performance driver for electronic systems. However, in traditional high-density CMOS circuits, rise in the junction leakage (doubling with every 10ºC rise in temperature) will become a significant source of power dissipation. At high temperatures reliability degradation mechanisms such as metal electromigration and time dependent breakdown of dielectrics will become limiting factors. The consideration for small leakage current and reliability factors limits electronic integration technology choices for high temperature to SOI CMOS and SiC. Honeywell Corporation offers a limited line of high temperature integrated circuits that are made of Partially Depleted (PD) SOI CMOS technology. At the same time, more complex and lower leakage CMOS circuits can be fabricated using Fully Depleted (FD) SOI CMOS. For temperatures above 250ºC small scale ICs using SiC devices are showing significant potentials. Also emergence of solid state vacuum transistors may enable the construction of small scale integrated circuits at temperatures above than 350ºC.

Wide Temperature (-180ºC to 110ºC) ASICs: For environments such as the moon and Mars, electronic circuit solutions will have to include the impact of the wide temperature swing. Wide temperature swing mainly impacts the performance of the mixed signal electronics circuits [4]. The change in the performance of mixed-signal circuits can be corrected using companion digital circuits and look up tables. Alternatively an aggregate set of analog circuits with optimized performance for specific narrow temperatures can be multiplexed as a function temperature to produce a wide temperature mixed-signal circuit. Wide temperature swings also result in large stresses within the electronics module due to differences in the coefficients of thermal expansion between the different construction materials. These stresses result in fatigue failure with cycling.

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