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Development of a K3A Robot for Deployment in Radioactive Environments

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ABSTRACT

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Radioactive materials make up a significant part of the hazardous-material inventory of the United States Department of Energy. Much of the radioactive material will be inspected or handled by robotic systems that contain electronic circuits that may be damaged by gamma radiation and other particles emitted from radioactive material. To use a mobile robot in the vicinity of high-level gamma radiation requires a special design. Since materials and electronic circuits can withstand some radiation without failure, the simplest approach would be simply to use an unmodified commercial mobile robot in the radioactive environment but remove it before failure occurs. Unpowered backup is another method of extending system lifetime in an ionizing radiation environment. When the primary system fails or degrades sufficiently, the backup system can be switched in to maintain system operation. By careful design and production-lot testing, systems can be designed to meet moderate doses of radiation; however, randomly-selected off-the-shelf commercial parts cannot be guaranteed to meet a specified total-dose tolerance. We can define the Basic Radiation-Hardened System to be a teleoperated K3A transport capable of deploying a radiation-hardened video camera for initial entry and inspection applications. The electronics in the K3A mobile base has three essential modules:

- MA-2 Motor Amplifier Circuit
- Drive Control Computer
- DC/DC Converter for powering the electronics.

Design of the system will be discussed.

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Introduction

The fact that nuclear radiation can shut down electronic systems became very obvious in 1962 when the Telstar I satellite failed as a result of radiation in the Van Allen Belts.[1] Since then the development of devices resistant to radiation has been driven by satellite, space, or weapons requirements. Teleoperated devices or robots for use on the earth's surface around radioactive materials are also subject to damage from ionizing radiation; however, the radiation environment is not an exact match to either the weapons or the space/satellite environments and the potential solutions to the semiconductor selection problem for earth-bound robots may be different. Much of the radioactive material will be inspected or handled by robotic systems that contain electronic circuits that may be damaged by gamma radiation and other particles emitted from radioactive material. Except for the immediate vicinity of nuclear reactors, gamma radiation is the predominant terrestrial nuclear product that can affect materials and electronic circuits. Alpha and Beta radiation are largely shielded by relatively thin containers; however, a significant amount of lead would be required to provide adequate shielding from gamma radiation from Cobalt-60. It can be concluded that shielding is not practical in most circumstances. Electronics that must be placed in the vicinity of moderate to high-level gamma emitters must be naturally radiation tolerant or should be radiation hardened to ensure operation for a prolonged period of time.

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[1] D. S. Peck et al., "Surface effects of radiation on transistors," *Bell Syst. Tech. J.*, vol 42, p95, Jan. 1963.

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Metal oxide semiconductor (MOS) technology has been the foundation of the very rapid growth in the development of integrated circuits based on very large scale integration (VLSI). Of particular importance are Complementary MOS (CMOS) digital circuits which require very low operating power. Most modern microcomputers are manufactured using CMOS technology. For these reasons the effect of radiation on CMOS devices is extremely important for robotics. The silicon-on-sapphire (SOS) and silicon-on-insulator (SOI) technologies are variations on the basic CMOS technology.

Without devoting any significant effort to understanding basic semiconductor physics, it can be pointed out that silicon-dioxide layers are used for insulation in the manufacture of MOS integrated circuits. In particular, the "gate" is insulated from the "channel" in MOS field-effect transistors (MOSFETs) used in VLSI digital logic. A buried oxide layer is also used between active elements and the silicon substrate of SOI devices. While some radiation effects occur in the region of silicon junction (and cause the gain effects found in TTL logic), most radiation damage in MOS devices is due initially to the formation of ion pairs when radiation deposits energy in the oxide layers.

Hardening Defined

What is radiation hardening? From the simplest viewpoint, hardening amounts to changing all components of a system that are affected by radiation to components that can withstand a significant radiation dose without failure. Structural materials, lubricants, elastomers, plastics, and, of course, electronics are all to be considered. However, in this paper it is useful to broaden the definition to include even complete changes in design, rather than a simple component change, as an alternative approach to hardening.

Alternative Designs for Robot Survival

There are few scenarios where radiation will cause immediate failure of electronic systems. (Only military applications come to mind.) Usually failure occurs only after exposure to radiation for an extended period of time. It can be seen from Table 1 that the Radiation Tolerance Requirement is a function of time. In space a requirement for high radiation tolerance is a result of very long missions where electronic circuits are exposed to relatively low levels of radiation dose rates, but where it is very difficult or impossible to repair the equipment. Robots in a terrestrial application may be exposed to higher levels of radiation; however, the radiation-hardness total-dose design requirement is really a function of the expected life of the system. The total radiation requirement shown in Table 1 is based on a 10,000 hr operational lifetime which is only a little over one year of continuous use in a radiation environment.

Since materials and electronic circuits can withstand some radiation without failure, the simplest approach to operation in a high radiation field would be simply to use an unmodified commercial mobile robot in the radioactive environment but remove it before failure occurs. This was tried at Chernobyl and a number of mobile robots failed prematurely since it was not possible to know precisely how long an unprotected robot could operate before failure.

	Common Dose Rates rad h^{-1}	Operational Life time hrs	Radiation Tolerance Requirement rad(Si)
Fuel Fabrication	10^{-1}	10^4	10^3
Cell Decontamination	10^3	10^4	10^7
Reactor Decommissioning	30	10^4	3×10^5
Fuel Processing	10^3	10^4	10^7
Fuel Handling	10^4	10^4	10^8
Underground Storage	10^3	10^4	10^7
Reactor Incident Inspection (TMI recommendation)			3×10^8

Table 1. Equipment Radiation Tolerance Requirements for several scenarios.[2]

Shielding is sometimes suggested; however, a significant amount of lead would be required to provide adequate shielding from gamma radiation. Depending on the energy spectrum of the emitted gamma radiation, Cobalt-60, for example, requires a lead shield over 4 cm thick to attenuate the exposure by one decade. Cesium-137, another common waste product, requires a 2 cm lead shield to attenuate exposure by same amount. It can be concluded that shielding is not practical in most circumstances.

Some semiconductor technologies have an inherent tolerance to ionizing radiation. Bipolar semiconductor devices may tolerate relatively high levels of radiation without failure; however, the gain is generally degraded considerably. Special circuit designs would be required to insure acceptable functionality when exposed to high levels of radiation. In addition, bipolar devices require considerable power for operation and are not generally suitable for computers or logic designed for operation in mobile battery-operated applications. Gallium-arsenide devices are also inherently resistant to damage by ionizing radiation. Some gallium-arsenide semiconductor components have been designed for military or space applications; however, they are expensive and a broad family of parts to meet design requirements are not available.

Unpowered backup is another method of extending system lifetime of electronic modules in an ionizing radiation environment. Unpowered CMOS circuits are able to tolerate much higher doses of radiation than circuits in actual operation. The survival dose of a total system can be doubled by keeping an unpowered backup system in reserve. When the primary system fails, or degrades sufficiently, the backup system can be switched in to maintain system operation for an additional period of time.

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[2] R. E. Sharp and D. R. Garlick, *Radiation Effects on Electronic Equipment: A Designers'/Users' Guide for the Nuclear Power Industry,* The Radiation Testing Service, AEA Technology, Oxfordshire, UK, 1994.

Finally, taking a somewhat radical approach, one could design a back-up system that would replace all the drive and control electronics with relay logic. Using relay logic, drive and steering motors could be operated under manual control to recover a mobile robot with a failed electronic control system. Relays and motors will continue to operate after a total dose of ionizing radiation in excess of 100,000 Gy (10 Mrad). Vidicon-based black-and-white video cameras are available with a similar radiation tolerance that will provide the necessary visual guidance for robot navigation.

A mobile robot is not likely to be continuously exposed to high levels of radiation. In addition, a mobile robot may be completely out of the radiation field for periods of time during which electronic modules could be replaced. The only essential requirement is that the total absorbed dose must be monitored so that failure does not occur when the robot is in use or when it cannot be retrieved for an electronics upgrade. The cost of the operational lifetime is the final bottom line irregardless of the number of electronics modules that must be replaced periodically.

Consider a mobile application in an underground storage facility. A dose rate of 10 Gy/hr (1000 rads/hr) would exceed 100 Gy (10,000 rad) total dose in less than one day of continuous exposure. It is likely that the dose rate would vary considerably during operation so several days probably would be required to reach a total dose of 100 Gy. Most modern COTS (commercial off-the-shelf) CMOS semiconductors will survive a total dose of 100 Gy. Thus one might be able to operate a mobile robot almost indefinitely by replacing soft or non-hardened electronics every few days. All of the basic control electronics of the Cybermotion K3A could be replaced for about $10,000. If one assumes that the electronics modules are replaced weekly, then the system could be operated for one year for a cost of $520,000 without any radiation hardening.

There are several problems with using off-the-shelf components. First, COTS components have no manufacturing controls for radiation tolerance and while most will meet the expected radiation tolerance without radiation screening, there is always going to be the odd-ball part that fails at 10 per cent of its expected tolerance. Second, COTS components lose TTL compatibility long before logic failure.[3] Finally, COTS components generally show a significant increase in leakage current well before component failure. This will result in system failure by overloading power supplies. Unexpected system failure is therefore a particular problem when using commercial off-the-shelf components in a system exposed to significant doses of radiation.

How hard to make it:

One can design circuits using circuits specifically processed to withstand high doses of radiation. Total-dose hardening to ionizing radiation is accomplished by using special manufacturing techniques that produce radiation-resistant circuits. (It should be noted that there are other effects of radiation due to nuclear particles and heavy ions that require other design modifications. Here we are limiting our discussion to damage due to gamma radiation.) Radiation-hardened CMOS components and microprocessors are being manufactured for space and military applications that remain functional after exposure to a total radiation dose of over 1E4 Gy (1E6 rads). Systems can be designed using such components but the individual components are much more expensive than non-hardened commercial components and the resulting system will be very

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[3] Andrew Holmes-Siedle, *MOS Technology in Nuclear Energy Environments: Tolerance to Radiation and Methods of Prediction*, Teleman Report No. TELEMAN/ENTOREL-REM-15-2, Radiation Experiments and Monitors, Oxford, England, 1994.

expensive. At a lower price and with a broader selection of parts, it is possible to obtain radiation-tolerant components with a lower assured performance such as 1000 Gy (100 krad).

Since the end of the "cold war" radiation-hardened semiconductor foundries have been shut down and manufacturers are discontinuing previously advertised hardness assurance levels. The Harris Corporation, one of the largest manufacturers of radiation-hardened semiconductors, no longer offers catalog semiconductor parts with a hardness specification of 10,000 Gy(Si) although the production processes have not been changed -- only the hardness assurance level. Products from discontinued foundry lines may continue to be available from other foundries.

When one considers economics, it may be *much* less expensive to develop electronics for a robotic system that will survive a dose of 1000 Gy rather than 10,000 Gy. Due to the requirements of space operation, commercially-manufactured modules are becoming available that have a hardness assurance rating of 1000 Gy. This level of hardness appears to be suitable for a majority of space and satellite applications. On the other hand, the 10,000 Gy hardened parts appear to be limited to military applications that are receiving less and less support. For a first cut at a cost estimate a 1000 Gy hardened design will be considered.

Hardening Electronic Circuits

Usually it is not possible to take a commercial design and simply substitute radiation-hardened components. In most cases a specific radiation-hardened design is necessary although it may be possible to work the other way and substitute commercial components for all or most of the rad-hard design to produce a less expensive equivalent system. Several radiation-hardened microprocessors are available. The microprocessor selection process has been considered previously.[4,5] Radiation-hardened logic families are available that may be used to re-design the electronic circuitry in K3A robot.

The motor-drive power amplifiers must be completely re-designed using radiation-hardened components. The current motor-drive electronics is a closed-loop control system that receives feedback from encoders mounted on the drive motor and the steering motor. Encoders include semiconductor circuits that use light-emitting diodes (LEDs) and photo transistors that are sensitive to radiation, therefore the encoders must be replaced with components that are either inherently insensitive to radiation or are specifically radiation-hardened.

Operation of motors or other end-effectors that use significant power requires radiation-hardened components that can control reasonably large direct currents. Radiation-hardened Power Metal Oxide Semiconductor Field Effect Transistors (Power MOSFETS) fill this need. A variety of Power MOSFETS are available from the Harris Semiconductor with a total-dose hardness up to 1E4 Gy (1E6 rads) and the capability of switching currents up to 50 amperes. Based on suggestions in an earlier report[6] the University of Florida Department of Nuclear Engineering Sciences has developed a prototype radiation-hardened PWM Motor-Drive Amplifier.

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[4] F. R. Sias, Jr., Selecting microprocessors suitable for robotic applications in radioactive sites, *Proceedings of the Fifth Topical Meeting on Robotics and Remote Systems,* American Nuclear Society, Knoxville, TN, April 26-29, 1993.

[5] F. R. Sias, Jr., and J. S. Tulenko, Update on Radiation-hardened microcomputers for robotics and teleoperated systems, *Proceedings of American Nuclear Society 1993 Winter Meeting,* San Francisco, Nov. 14-18, 1993.

[6] Sias, Fred R., Jr., "Radiation Hardening Power MOSFET PWM Motor-Drive Amplifiers," Report prepared for the Department of Nuclear Engineering, University of Florida, Gainesville, April 22, 1994

DC-to-DC power converters are required to change and 24 volt battery power of the K3A to the regulated 5 volt supply required by the computers and digital control logic in the robot. Since the circuits required for the DC-to-DC converter are very similar to the PWM circuits used in Motor-Drive Amplifier design, a prototype power converter has also been developed at the University of Florida. In addition to the prototype developed at the University of Florida, a commercial radiation-hardened DC-to-DC converter is available from Advanced Analog, a Division of Intech. The unit price of a ART2815T DC/DC converter is $18,500. Specifications state that the MIL-STD module is radiation hardened to greater than 1000 Gy (100 krad). A paper by David K. Myers reported a demonstrated performance within specifications to 1.5E4 Gy (1.5 Mrad).[7]

Most passive electronic components have been shown to be tolerant of ionizing radiation in excess of 10,000 Gy. It is unlikely that passive components will present a design limitation as long as particularly susceptible organic compounds are not used for insulation or for encapsulating the parts.

Radiation Monitoring:

As described earlier, a mobile robot will usually operate in a radiation field that varies in intensity. Total dose effects are cumulative, consequently some means of monitoring total-dose exposure is necessary in any practical environment. The RADFET developed in the UK,[8] is a suitable sensor. Satellites International Limited developed the ESA Modular Dosimeter System for monitoring satellite absorbed dose. A modular system capable of monitoring up to 8 radiation-sensitive locations was originally delivered in 1988.

Cost Estimate

The cost of manufacturing a radiation-hardened version of the K3A inspection robot can be estimated by considering the following basic modules:

1. The mechanical structure
2. DC-1 Drive Control Computer
3. MA-2 Motor Amplifier
4. DC/DC Converters
5. Video cameras.
6. SPIKE board

Most of the mechanical system is aluminum or other metals, along with some plastic and elastic components. The metal structure is unaffected by exposure to radiation greatly in excess of the dose that would cause all electronic components to fail. Most polymers and elastomers are not significantly affected by radiation doses below 10,000 Gy (1 Mrad). Teflon is a unique exception and parts that include Teflon insulation must be replaced by parts using less affected insulation. For example, hookup wire with cross-linked polyolefin insulation is tolerant to a radiation dose of 1 MGy (100 Mrad).

Radiation hardening the electro-mechanical system amounts to initiating engineering changes to eliminate Teflon or PVC insulation or components and possibly replacing radiation-sensitive

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[7] Myers, David K., and Richard T. Miller, "Space Radiation Characterization of the ART2800 DC/DC Converter Family and 7846 Post Regulator."

[8] A. G. Holmes-Siedle and L. Adams, RADFET: a review of the use of metal-oxide-silicon devices as integrating dosimeters, Radiation Physics and Chemistry, 28(2) 235-244, 1986.

optoelectronic encoders used for navigation and steering. Position feedback for servo control of drive and steering may be obtained by using resolvers and a radiation hardened resolver-to-digital converter. The hardened slip-ring assembly, dc motors, and resolvers may be obtained from the Poly-Scientific Division of Litton Systems, Inc. in Blacksburg, VA. Natel Engineering Company, Inc. produces the HSRD1056RH resolver-to-digital converter that is radiation hardened to 1000 Gy (1E5 rad). Estimated cost of re-engineering the K3A base: $100,000.

The DC-1 Drive Control Computer can be hardened by two approaches. The module can be re-designed using radiation-hardened parts or a commercial microcomputer such as the Harris Standard Spacecraft Processor Module can be procured. Based on a similar design and the cost of radiation-hardened parts an in-house re-design could cost $180,000. The Harris processor module hardened to 1000 Gy (100 krad) can be procured for about $300,000.

The cost of re-designing and constructing a radiation-hardened version of the MA-2 Dual Motor Amplifier is estimated at $150,000. A DC/DC Converter can be procured from Advanced Analog for $18,500 and a radiation-hardened black-and-white video camera with non-browning, radiation tolerant lenses can be procured from Rees Instruments, Inc. for under $10,000. The SPIKE[9] board is a radiation-hardened re-design of a module that controls switching of backup modules when a radiation-induced failure occurs. A rough estimate of the incremental cost of re-designing a radiation-hardened K3A is about $600,000.

An alternative less expensive approach would be to leave the electronics un-modified and design an relay backup system that would automatically take control when the electronics fail and allow a tethered robot to be driven out of a hazardous area using manual controls. A radiation-hardened video camera would permit a remote operator to navigate under visual control. We have little reference data with which to estimate an all-relay logic design cost; however, we feel that it would be similar in complexity to a processor re-design without the radiation-hardened parts. An all-relay backup system would allow an operator to recover a Cybermotion mobile robot after radiation had caused complete failure of the electronic control system.

Conclusions

The Mobile Inspection and Survey Robot called ARIES is designed with commercial electronic components that are satisfactory for operation where total doses of gamma radiation are relatively low. Standard commercial semiconductors are likely to survive a total-dose exposure in excess of 100 Gy (10,000 rad). Low-level hazardous waste is stored in drums that emit a surface radiation dose rate of only 1 mGy/hr (100 mrem/hr) or less. However, an inspection or survey task near high-level Cobalt-60 emitters would require radiation hardening to avoid damage to the on-board control electronics.

Since over 4 cm of lead is required to provide a one decade attenuation of gamma radiation with the Cobalt-60 energy spectrum, shielding is not considered a feasible means of protecting all of the electronics on-board a mobile robot.

Radiation hardening a mobile robot requires a complete re-design of the electronic control system using specifically radiation-hardened semiconductor components. A robot with a total-dose hardness of about 1 kGy (100 krad) could be designed now; however, a 10 kGy (1 Mrad) design

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[9] SPIKE is a reliability enhancement board for Navmaster operation in gamma radiation environments. It was specially designed for an earlier Cybermotion robot at the Savannah River Laboratory.