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Original Article

Radiation tolerance of a small COTS single board computer for mobile robots

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A B S T R A C T

As robotics become more sophisticated, there are a growing number of generic systems being used for routine tasks in nuclear environments to reduce risk to radiation workers. The nuclear sector has called for more commercial-off-the-shelf (COTS) devices and components to be used in preference to nuclear specific hardware, enabling robotic operations to become more affordable, reliable, and abundant. To ensure reliable operation in nuclear environments, particularly in high-gamma facilities, it is important to quantify the tolerance of electronic systems to ionizing radiation. To deliver their full potential to end-users, mobile robots require sophisticated autonomous behaviors and sensing, which requires significant computational power. A popular choice of computing system, used in low-cost mobile robots for nuclear environments, is the UP Core single board computer. This work presents estimates of the total ionizing dose that the UP Core running the Robot Operating System (ROS) can withstand, through gamma irradiation testing using a Co-60 source. The units were found to fail on average after 111.1 ± 5.5 Gy, due to faults in the on-board power management circuitry. Its small size and reasonable radiation tolerance make it a suitable candidate for robots in nuclear environments, with scope to use shielding to enhance operational lifetime.

1. Introduction

The challenge of inspection and monitoring of nuclear facilities is present globally, with worldwide nuclear electrical generation capacity set to increase into 2050 [1]. This represents not only an increasing requirement to maintain existing operational and new-build fleets of nuclear facilities, but the significant commitment to appropriately manage retired sites, with the United Kingdom alone predicting a required financial commitment in excess of £130 billion over the next 120 years for decommissioning of legacy assets [2].

Robotics have been identified as a route for the characterization of legacy facilities as a cheaper, more reliable, and safer approach than traditional human led activities. For example the UK Nuclear Decommissioning Authority aims to reduce activities performed by humans in hazardous environments by 50% before 2030 [3], with the use of robotics a priority for research and development to support future activities [4]. Mobile robotic platforms have already seen adoption for inspection and incident response such as at Fukushima Daiichi Nuclear Power Plant where high levels of ionizing radiation may preclude human led activities altogether [5,6].

For stakeholders to expand their utilization of robotic systems and reduce human activities in high-risk scenarios, these solutions need to be affordable, reliable, and able to provide semi-autonomous behaviors to reduce the burden on human operators, particularly for scheduled operations. This work considers the scenario of long-term monitoring and inspection of higher activity waste packages in interim storage, which may span over 100 years. A requirement for these facilities is the continual monitoring of environmental conditions, facility structure and physical security, and of course the health of waste containers [7]. For future routine semi-autonomous inspection of interim stores and highly active waste containers, a robot must be able to perform the following operations in a highly reliable manner:

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- Estimate its location in a facility, typically using Simultaneous Localization and Mapping (SLAM)
- Perform path planning to specific waypoints
- Maneuver through the environment to reach these waypoints and perform inspection tasks
- Avoid contact with assets in a facility, i.e. obstacle avoidance
- Monitor its internal state and act accordingly, e.g. manage battery recharging, monitor total ionizing dose

The desire for autonomous or semi-autonomous behaviors represent a need for higher level computation ability for the robot. In fact, there is a growing precedent in the nuclear sector for robotics to be ROS (Robot Operating System) compatible [8–14], enabling quick and cheap development of systems, and therefore a system destined for nuclear inspection should try to maintain this approach. This demand for higher level behaviors necessitates the use of modern, reasonably powerful, computing hardware.

A major advantage in the use of robotics is their inherent radiation tolerance of materials and circuitry in comparison to humans, however, this is not limitless. To provide higher level robot autonomy, the more complex electronic processing and circuitry required are expected to be generally less robust to ionizing radiation than more simple control hardware. Though the actual ionizing radiation levels of specific interim storage facilities are not disclosed, rates on the order of 100 mGy/h ($\approx$ 10 μGy/s) are considered here as representative for terrestrial nuclear inspection [15–17]. Gamma-rays are likely the primary source of significant radiation exposure to robotic systems, as they are most prevalent and have been the normal benchmark for most robots [5]. For simplicity, it is assumed a robotic platform would perform a daily 5-h routine inspection, 5 days a week at a constant exposure of a substantial 100 mGy/h rate, with locations available for the robot to retreat to with negligible exposure between inspections. Further assuming a requirement of 50 weeks operation a year yields a daily dose of 0.5 Gy/day, a weekly dose of 2.5 Gy/week, and an equivalent annual dose of 125 Gy/year. The actual necessary return on investment time would be defined by nuclear sector stakeholders, however, for this work an operational lifetime of one year will be examined.

For other radiation conscious robot designs such as interplanetary rovers, radiation hardened processing units are employed. Though it may be possible to run ROS features on these low computation power devices, the sheer financial cost estimated to be three orders of magnitude of that of consumer equivalents [18,19] prohibits the use of a specifically designed radiation tolerant computing unit. The harsh environments anticipated for nuclear inspection, the expected short lifetime of a robot, and the mandate to reduce public spending prohibits the use of costly radiation tolerant devices.

The UK nuclear sector has communicated an aversion to single-use bespoke solutions, in preference of Commercial-Off-The-Shelf (COTS) or Modified-Off-The-Shelf (MOTS) technologies to be used as expendable elements in more flexible systems, providing cheaper and higher technology readiness level products quicker [8]. This effort to reduce cost and maintain a more disposable robot unit is in keeping with a global shift in nuclear inspection robotics, such as aquatic robots designed for deployment at Fukushima, Japan and Sellafield, UK [20,21]. For mobile robotics to deliver added benefit to the nuclear sector globally in a timely manner, this motivation for rapid and low-cost deployment needs to be satisfied, therefore, only the use of affordable and ubiquitous COTS components will be considered in this work.

This poses a challenge to nuclear sector stakeholders and robotics engineers who wish to deploy more sophisticated systems to tackle unique challenges, whilst maintaining reliability and at a reasonable price point. It must be assessed whether COTS computing devices provide both the necessary computational power to carry out autonomous behaviors and radiation tolerance to have a meaningful lifetime in harsh environments.

To this end, this work explores the radiation tolerance of a COTS AAEON UP Core single board computer (SBC) as a suitable option for the current generation of robotics intended for nuclear deployment. Section 2 describes the rationale behind choosing the UP Core SBC as well as the experimental procedure for irradiation of multiple devices. Section 3 presents empirical estimates of total ionizing dose (TID) for the Up Core SBC and diagnosis of the fault condition observed.

2. Method

The UP Core SBC was chosen based on numerous criteria, however, both its sufficient computational power to run Linux and necessary ROS components and more importantly its small footprint lends itself to this application. Where radiation hardened processors and associated components may offer a rating on the order of 1–10 kGy [22], literature suggests that non-hardened processing and microcontrollers may only provide on the order of 100 Gy of tolerance [17,23–25]. Therefore, to match the similar tolerance of specialist hardware with COTS solutions and provide at least one year of operation in the hypothetical nuclear environment proposed (125 Gy/year), shielding may be necessary to provide additional protection. Minimizing the footprint of components can dramatically reduce the overall mass of such a shielded container, hence the use of the smallest available SBCs is a priority.

The UP Core SBC [26] has an Intel Atom® x5-Z8350 quad core processor, up to 4 GB of DDR3L 1600 MHz memory and up to 64 GB of eMMC storage depending on configuration, whilst boasting a diminutive footprint of only 56.5 mm × 66.0 mm. The low power consumption of only 13 W typical, requiring only passive cooling, input voltage of 5 V nominal, connectivity such as in-built WiFi and numerous I/O options, and low mass make it suitable for prolonged robot deployment where battery use may be a consideration. A picture of an UP Core board can be seen in Fig. 1 with dimension

Fig. 1. UP Core single board computer, with aluminum passive heatsink and connectors for various I/O. Board dimensions 56.5 mm × 66.0 mm.

indications.

Though some Raspberry Pi SBC variants have received interest as low cost replacements for computing in harsh environments [27], it is anticipated that current models may lack computational power to handle current and future sophisticated algorithms, and present issues around reduced data rates from multiple sensors, such as depth cameras and 3D lidar. Nuclear deployed robots such as MallARD [28], MIRRAX [29], and Vega [30] which traditionally used diminutive Raspberry Pi products now use AAEON UP SBC variants as a more powerful but compact alternative. As AAEON UP products are already in use in nuclear deployed robotics, there is direct motivation to test them with respect to radiation tolerance.

To assess the TID limits of the UP Core SBC, multiple units were exposed to a Cobalt-60 source whilst powered and running various routines. As the robot is expected to be ROS compatible, all routines were designed around the ROS framework, i.e. each test was built as a ROS node with publishers and subscribers of ROS topics, with data recorded locally to the Device Under Test (DUT) and an external PC concurrently. The apparatus used was a Foss Therapy Services Model 812 Cobalt-60 self-shielded irradiator operated by the University of Manchester Dalton Cumbrian Facility, UK. This unit consists of up to three Co-60 rods which can be engaged inside a sealed enclosure, with two serpentine access ports.

A schematic of the experiment is provided in Fig. 2. Each DUT was supplied by an external 5 V power source, with the total current draw monitored and recorded externally. The DUT had connection to USB flash memory outside the irradiation chamber via a generic USB 3.0 extension cable for device localized data recording, and the stock WiFi dipole antenna was placed outside the heavily shielded irradiation chamber using an appropriate 2.5 m extension. As can be seen in Fig. 3 the DUT was placed with the largest surface area normal to the photon flux (originating from the three rods at the rear of the irradiation chamber), with the aluminum heatsink downstream of the photon flux.

Each DUT was held in an identical 3D printed PETG (polyethylene terephthalate glycol-modified) plastic holder, which slotted into a fixed receptacle in the chamber to ensure each test was performed at the same orientation and distance from the source. PETG was chosen as it is more radiation tolerant than more common PLA (Polylactic Acid) material [31,32].

Before irradiation, each DUT had been operated with the test suite of ROS nodes for at least 24 hours continuously, and was also operated for between 10 and 20 minutes inside the closed irradiation chamber prior to irradiation to gather a baseline of performance in-situ. Tests included monitoring of current demand, CPU core temperatures, USB communications and ROS data logging, WiFi communications including ROS messages, a timing indicator, and a checksum test of image files in storage. All messages on all topics were recorded to rosbag files both to the USB flash memory by the DUT and by the external PC utilising the WiFi connection between them, with the ROS master being hosted by the DUT, in case of loss of WiFi connection during irradiation. All DUTs used Ubuntu 18.04, with ROS version Melodic.

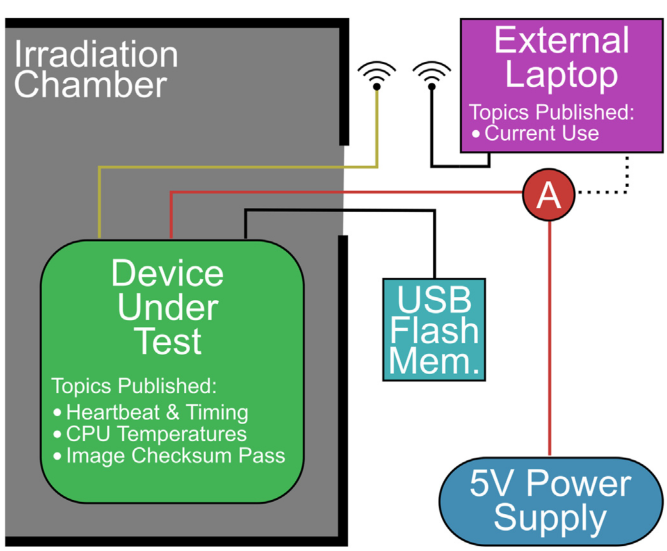

Fig. 2. Schematic of data and power connections to DUT. External laptop was connected via USB to the digital ammeter for current monitoring.

Fig. 3. DUT located in the irradiation chamber with external connections to WiFi, USB, and power from left to right at the top of the unit. The locations of the three Cobalt rod sources when in operation are visible to the rear of the chamber.

3. Results and discussion

Table 1 shows the individual total accumulated dose for each of the DUTs in this work. The rate was reduced from 0.56 Gy/s (in accordance to MIL-STD-883-1, 1019.9 [33]) to 0.136 Gy/s through removal of the central Co-60 source rod and introduction of a tungsten attenuation layer to yield an approximately x4 attenuation factor. This reduction in dose rate allowed for better temporal resolution of the point of failure, therefore more accurate estimates of total dose within a timing error of ±3 seconds based on Co-60 rod engagement delay [34]. Time to failure was measured using the timestamp of the last "heartbeat" message (published at 1 Hz) recorded by the external system via WiFi from the DUT.

The average total ionizing dose at failure was 111.1 Gy with a standard deviation of ±5.5 Gy. These absolute values are subject to a

Table 1
Total ionizing dose before failure of SBC devices.

Serial No.	Dose Rate (Gy/s) ±4%	Time to failure (sec) ±3 s	Ionizing Dose Failure (Gy)
C19816966	0.560	200	112.0 ± 1.7
C19816965	0.560	209	117.0 ± 1.7
C19816964	0.136	758	103.1 ± 0.4
C19816952	0.136	844	114.8 ± 0.4
C19816951	0.136	799	108.7 ± 0.4

systematic ±4% uncertainty from the in-situ dose rate calibration estimate performed using a Radcal 10X6-0.18 high dose rate ion chamber for both rates used, situated at the same location as DUTs. In all instances, the current demand from the device dropped suddenly, with no prior indication of intermittent faults. This behaviour was seen across the small range of dose rates used in this investigation, though this may not hold for extremely high or low rates, and further investigation would be required for a specific deployment scenario.

Fig. 4 shows the current draw for a board (Serial: C19816964) during irradiation, it can be seen that the current demand begins to fall immediately after the last ROS message is recorded by the DUT. ROS messages originating from the DUT recorded locally and received externally stop at the same time across all ROS topics, indicating a total system failure, such as a critical CPU, power, or memory fault rather than a degradation in WiFi communications or IO. No devices could be revived through performing a power cycle, suggesting it was not an intermittent or temporary fault condition. However, post irradiation, by increasing the input voltage above the nominal 5 V, some devices were once again fully operational, indicating that a fault had occurred in the power management circuitry of the SBC.

It is known that voltage regulators are particularly vulnerable to radiation induced damage, with a reduction in output voltage as a function of total dose [16]. To investigate if the on-board voltage converter (Monolithic Power Systems MP8762E) degradation was the cause of the premature failure of the devices, the voltage was recorded for irradiated devices at increasing input voltage until they could successfully boot and perform the same computations run during irradiation testing. This was compared to the output voltage provided by SBC units which had not undergone radiation exposure.

Fig. 5 demonstrates how all of the irradiated DUTs required higher input voltages to activate the system than a non-irradiated example (serial: C19817007). The required higher voltage appears to increase with total received dose. Some irradiated DUTS were left in the irradiator following failure and hence received total doses beyond the ≈110 Gy dose at failure. This may indicate a general threshold voltage modification or other radiation damage phenomena of the internal MOSFET (metal-oxide semiconductor field effect transistor) devices [35]. Device C19816966 received a total dose of ≈338 Gy, and it was not possible to boot despite increased input voltages up to 6.00 V, indicating a subsequent unknown component failure.

When the input voltage is below the activation voltage, the SBC powers down, therefore during irradiation, the nominal 5 V input voltage becomes insufficient and hence a full system failure occurs. By providing a greater driving voltage during irradiation, it may be possible to prolong the life of the system beyond the ≈110 Gy TID demonstrated. This confirmation of vulnerability associated with the voltage converter indicates that other components on the SBC have a TID beyond that of the ≈110 Gy demonstrated by the voltage converter.

To include an additional safety factor of 50% for deployment [34], the equivalent allowable dose to a board under operation is ≈ 74 Gy. Including this safety factor necessitates the use of strategies to increase the TID of the SBC to reach the 125 Gy annual target.

Modification to the power management design could render increased radiation tolerance overall, however, the component density and complexity of the Up Core SBC may result in it being more effective to preferentially shield the most vulnerable components rather than expend time and cost to design an alternative. As discussed, by specifically running the SBC at a greater input

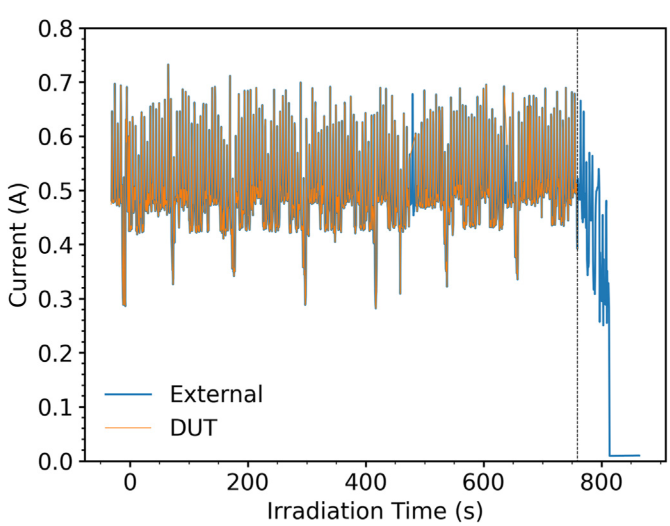

Fig. 4. Recorded current use for both DUT and external rosbag data. Correlation is evident between DUT no longer receiving external ROS messages and drop in current draw, indicative of DUT shutdown sequence. Device serial: C19816964.

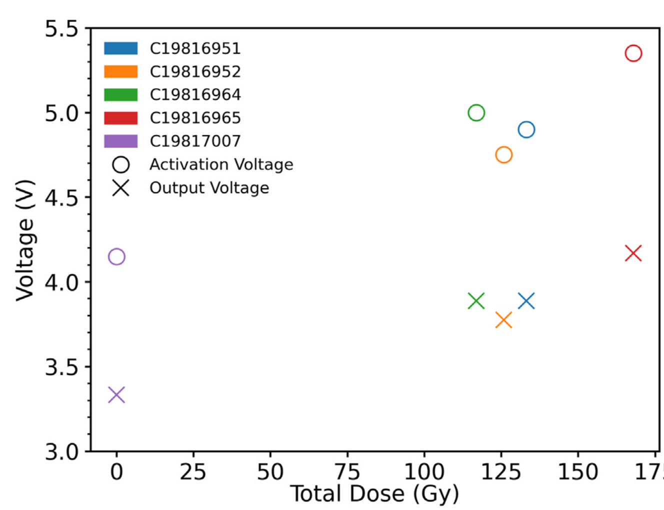

Fig. 5. Input voltage required for SBC boot (open circles) and voltage output from on-board voltage converter at boot (crosses).

voltage to overcome radiation induced effects may lead to downstream components such as the on-board power management IC (Texas Instruments SND9039) to be operating out of specification, due to higher output voltages, and become electrically damaged. This is seen in Fig. 5, where the desired voltage output is 3.3 V, but irradiated units may provide in excess of 4.1 V. With modification to the SBC, it can be possible to monitor voltage converter output either to modulate the input voltage, or set a bound at which a robotic platform is deemed unreliable and must exit the hazardous environment for replacement, repair or disposal.

The most readily available mitigation strategy is the use of shielding, with materials such as tungsten or lead being incorporated to increase operational lifetime. To increase the allowable TID from 74 Gy to 125 Gy, it is necessary for the shielding to reduce the dose by $\approx$ 40%. Tungsten will be considered here, as it has closer thermal properties to the heatsink material aluminum compared to lead, therefore the shielding enclosure can also form part of the thermal management. Gamma emission from Cs-137 is the most relevant to the radiation fields at the Fukushima and Chernobyl sites, with an energy of 0.66 MeV. As shielding thickness is a function of photon energy, 1.2 MeV photons for the Co-60 irradiator will also be assessed.

A theoretical UP Core SBC is enclosed by shielding material with an internal cavity of 68.0 mm $\times$ 63.0 mm x 20.0 mm, allowing for clearance and space for cable routing internally. With values for mass attenuation coefficients [36], a density of Tungsten of 19.3 g/cm^3, and a simple Beer-Lambert approximation, the required thicknesses are $\approx$0.27 cm and $\approx$0.63 cm for Cs-137 and Co-60 respectively. Using a thickness of 0.63 cm, the total shielding mass for a simple cuboid is $\approx$ 2.2 kg. As historically most deployment scenarios have not exposed a robot to higher photon energies associated with Co-60 sources, shielding mass may be reduced, for example for a Cs-137 dominant environment the mass would be 0.8 kg.

Regardless of the eventual shielding design, this additional mass may or may not be feasible for some platforms. Ultra-compact platforms [30] would be wholly unsuited to this approach, both due to the increased physical footprint and the additional mass. Larger platforms [13–15,17], may be better suited for this approach. Shielding is not a panacea and cannot be continued indefinitely, as eventually mass will out-pace the payload capability of any robotic platform. To deliver an order of magnitude protection of 1 kGy for the UP Core, in a Cs-137 dominant environment, the mass increases approximately eight-fold to 6.25 kg. For a 10 kGy suitable enclosure the mass is 17.4 kg, practically the entire payload capacity of common mobile robot platforms such as the Clearpath Jackal UGV (20 kg). Shielding for mobile robotics is ideal for small to moderate improvements to TID specifications but becomes infeasible to deliver large increases over multiple orders of magnitude. Even with additional shielding, it may not be possible for the UP Core to compete with specially designed radiation hardened systems due to this mass limitation at very high TID requirements.

Where shielding is unsuitable for a platform or undesirable due to additional cost and manufacturing requirements, end-users may simply choose to replace the computing unit more frequently than the annual cycle supposed in this work. At a low cost of <150 GBP ($\approx$190 USD), it is a trivial expense to replace a computing unit well before any expected failures as a result of accumulated ionizing radiation exposure, with no modification required. However, despite the low cost to replace hardware, there are associated costs to end-users for manual retrieval, decontamination, and replacement of components which may significantly impact running costs. There are also additional risks to radiation worker health which would need to be considered. Ultimately, the additional cost and risk associated with maintenance and replacement must be factored into a full cost/benefit analysis by end-users.

4. Conclusions

To deliver smarter and cheaper mobile robotic systems to the nuclear sector, more powerful COTS computing is required which can provide sufficient radiation tolerance to deliver meaningful operational lifetime in moderate radiation environments. The UP Core single board computer investigated in this work has a measured total ionizing dose of 111.1 $\pm$ 5.5 Gy when placed in a Cobalt-60 irradiator whilst running ROS software and communications.

An under voltage condition caused by ionizing radiation induced damage to the on-board voltage converter is the likely failure mode in this instance, where an increased input operating voltage above nominal 5.0 V can enable continued operation of the UP Core SBC units beyond 111.1 Gy TID, however, at greater total dose (between 168 and 338 Gy) the SBC is unrecoverable. The small footprint of the UP Core allows for shielding to be readily installed around vulnerable components, such as the voltage convertor, to prolong operational lifetime with minimal additional mass. Its low cost means end-users can easily replace damaged units, however, this must be balanced against the projected costs of manual retrieval of possibly contaminated systems from active environments. These results indicate that the UP Core SBC is a suitable candidate for robotic inspection of interim waste stores and other nuclear environments, with little to no modification.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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