# Measuring the Degradation of Robot Components Caused by Gamma Radiation

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BRIEF. Individual component radiation testing is an effective way to gather data for the development of modeling software to predict a system's radiation response.

ABSTRACT. Comprehending total effects of radiation on robotic systems used to clean up nuclear disasters depends on radiation responses of each component which often result in faulty system performance. There are significant amounts of research done to understand the radiation response of individual components; however, little has been done to quantify the interaction of degraded components and resulting system fault modes. The MCC 7805CT linear regulator and QTR-8A reflectance sensor on the Pololu robot were tested to quantify their total ionizing dose responses using a Cs-137 irradiator. The fluctuation in output voltage and current for the regulator and output voltage for the sensor were measured at each increasing exposure interval. Standard curves were calculated by fitting the current and voltage versus total dose for each of the components. A slight decline was observed in both the output voltage and current while an increase in the values from the sensor. Results from this testing will be incorporated in a larger attempt to model how the simultaneous degradation of both parts will affect one another by using a Bayesian Network (BN) model. This approach allows for modeling total system performance, diagnosis of fault modes from degraded components, and potentially will assist in time-to-failure analysis.

## INTRODUCTION.

Nuclear accidents initiated by environmental events, such as Fukushima, pose an urgent threat to public health and environmental safety. Moreover, post-nuclear accidents create a need for technologically advanced robotic systems that can gather and communicate data about the extent of the radiation damage, eliminating the need to expose humans to these harsh radiation environments. However, electrical components are not immune to the effects of radiation. High energy photons and energetic particles present after a nuclear catastrophe can degrade electrical components and result in system malfunctions, data corruption, or total system failure[1],[2].

There are two approaches to understanding and the eventual mitigation of the radiation effects on a system. Typically, the entire system is irradiated in a controlled environment to understand overall system function at specific exposures, but the underlying cause of the system failures is unknown and prognosis is not possible. Another approach includes the testing of individual components in a controlled ionizing radiation environment to determine their specific performance after cumulative exposure[1][2]. Testing individual components alone does not allow for understanding higher system performance degradation. This work combines the individual component testing approach along with a basic Bayesian Network (BN) model. Data from controlled exposures can reliably predict how these robotic systems will execute the tasks desired with irradiated components.

One research extension based on this radiation testing is the Pololu robot research. The Pololu robot is a small programmable robot that follows the simple command of following a line in a circle. Past research has introduced irradiated components to the Pololu robot to determine the degraded components' effects on the expected performance of the circuit and the system behavior[2]. This work extends previous research by testing a linear regulator and reflectance sensor to determine how the output voltage and current from each component changes when irradiated. Degradation is modeled where the model parameters can be used to calibrate the BN for prognosis. The linear regulator takes an unregulated input voltage and reduces variation by using an internal reference voltage. However, when irradiated, the internal voltage is altered and is no longer able to maintain the output voltage for the circuit that is needed to keep it functional. The reflectance sensor detects the environment and guides the robot's movements by following a solid black line[3]. These tests help to gain an understanding of the complex interactions of the parts and how the radiation responses lead to the system's failure[2]. This research and other research similar to it understands the characteristics of Total Ionizing Dose (TID) for each individual component which measures the cumulative radiation dose that affects the component, and focuses specifically on gathering values that represent how these components will affect different systems based on their dose response.

An extension of this research included the development of a Bayesian network model that would convert the raw data gathered into graphical representations that exhibited the behavior of both components if irradiated in the same circuit. Bayesian Network models use Bayes' theorem which is a method of calculating the probability of an event occurring given information about another dependent event[2]. In previous research, Bayesian Networks have been applied to determining the effects of ionizing radiation environments on single components as similarly done here[4]. Information produced from these models expresses not only the raw data, but also 20,000 other possible points or potential behaviors that the linear regulator and reflectance sensor could exhibit if tested simultaneously. The BN models developed here can be extended and used prior to the deployment of these robots, to understand and potentially mitigate radiation-induced system failure. This approach also has the potential to enhance the ability of on-site experts to make informed decision by using probabilistic models founded on real-time data[2].

## MATERIALS AND METHODS.

The linear regulator was tested to understand how the output voltage and current vary after exposure to TID. Two separate circuits were built to conduct the experiment for the linear regulator and the reflectance sensor from the Pololu robot. A DIP switch containing eight switches was separately wired to the Arduino analog pins to connect the electronic component. Five resistors used to simulate different load conditions could be selected through the DIP switch. A DIP switch is an arrangement of switches in a dual in-line package used to select an operating mode of a device. The experimental setups of the linear regulator and reflectance sensor are shown below in Figure 1. Different resistive loads determine the supply current for the linear regulator, corresponding to 20 mA to 60 mA (10 mA intervals), and model the Pololu robot's power consumption. As the robot speeds up or slows down the amount of current required by the system changes and the linear regulator is required to produce a constant voltage under these varying conditions. A current sensor was also incorporated into the circuit to measure and transmit the fluctuation of the current to the Arduino. The reflectance sensor circuit only contained the wire connections directly from six of the eight LED/phototransistor pairs to the analog pins in Arduino.

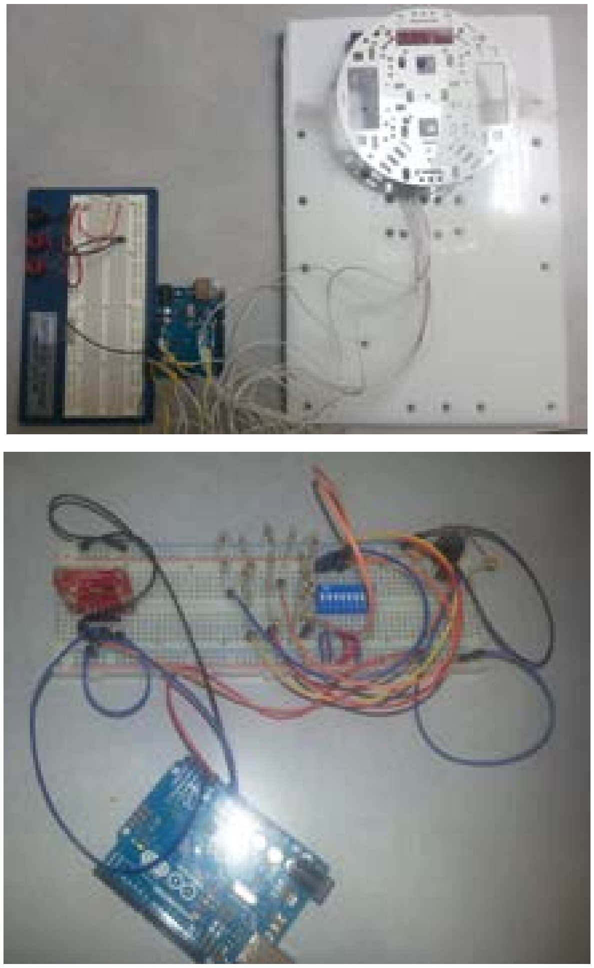

**Figure 1.** The experimental setups for the two components were vey different with the reflectance sensor being mounted in order for to be irradiated, while the DIP switch was used to test the linear regulator which was irradiated by itself.

An Arduino Uno microcontroller was used to report the resulting analog values to a computer interface. The programming of the Arduino for the linear regulator required the DIP switch and the current sensor analog pins to be read and recorded on the screen ten times with a delay of one second between each reading. The component was irradiated and then removed from the irradiator and placed into the circuit to be tested. Each of the five current loads was tested subsequently before the linear regulator was removed to be irradiated again. The reflectance sensor's programming in Arduino was more straightforward due to the lack of additional parts in its circuitry. The only commands used included reading and writing the analog values to a serial monitor from the analog pins. With these commands, ten measurements were recorded with a delay of one second between each reading at each tested radiation dosage.

A major issue encountered with conducting simple analog commands is that Arduino does not possess the ability to save the values that are read and recorded to a serial monitor. Therefore, the software known as Putty was connected to the Arduino coding in order for the analog values to be written into a comma separated values text file (.csv) that could be saved and reopened in Microsoft Excel for analysis.

An additional test was done with the reflectance sensor to determine its response when placed in the same circuit with a degrading linear regulator. The sensor was not irradiated, only had two LED/phototransistors, and was connected to a power supply that would be used to decrease the input voltage. The input voltages tested were: 5 V, 4.9 V, 4.8 V, 4.7 V, 4.6 V, and 4.5 V which were determined from the analysis of the linear regulator in the earlier tests. The sensor was tested still attached to the Pololu robot frame, but was placed over a black surface instead of a white surface to determine the impact of the reduced input voltage on the peak output of the line sensor.

Each of the components was irradiated with a Cs-137 source that emits gamma radiation at approximately 700 keV from a cesium rod. The dose rate, the rate that parts are exposed to ionizing radiation, is controlled by decreasing or increasing the distance of the parts to a source. Dose rate was calculated accurately fom a formula derived fom previous experiments in this irradiator performed by a Vanderbilt research group. The linear regulator was irradiated separately from all other circuitry to limit radiation degradation to the regulator. While being exposed to ionizing irradiation the regulator was powered using a breadboard at 15 V from an external power source to model the robot under a nominal use case conditions that would be representative of its use after a radioactive disaster[3].

The linear regulator was exposed to increasing amounts of irradiation ranging from 20 krad to 180 krad at a dose rate of 780 rad/min. The irradiation testing for the reflectance sensor differed from the linear regulator in that the component was attached to the frame of the Pololu robot and hovered over a white surface at the distance from the ground that it would be secured at if the robot was fully built. The sensor was exposed to 20 krad to 100 krad at a dose rate of 600 rad/min. As mentioned above, only six of the eight sensors were tested, which left two sensors that were covered in order to block any possible interference.

## RESULTS.

As predicted for the linear regulator, degradation in the functionality of the linear regulator was observed in response to the TID conditions. According to the manufacturing company, the threshold for faulty behavior in the MCC 7805 CT linear regulator occurs at an output voltage below 4.8V. Between 40 krad to 60 krad, the output voltage from the components dropped below 4.8V and as far as 4.6V. Figure 2a shows how the output voltage from the linear regulator changed as the radiation exposure increased. For four out of the five resistive loads this response was detected. However, the 20 mA load demonstrated a non-monotonic change in output voltage. Starting at 100 krad the output voltage increased quickly to 5V, until 140 krad, where the voltage then decreased and remained at 4.8V. The output current measured from the degraded linear regulator remained relatively steady and within a reasonable distance from the targeted resistive load. Figure 2b shows the behavior of the output current as the radiation exposure increased. There was a slight decrease at 120 krad for four of the five loads, but the 20 mA load demonstrated a fault mode. The output current at this switch decreased drastically from 20 mA to 2.4 mA, which is indicative of a complete failure of the linear regulator.

One failure mode of the reflectance sensor is defined as resulting in a false positive, in which the sensor's output values increase to values that attributed to a darker surface. This trend can be seen in Figure 3 where all of the sensor output values began to increase starting immediately at 20 krad. The sensors that were closer in position had similar responses to the radiation creating similar curves as shown in Figure 3. Sensor six displayed the strongest behavior with its output values increasing from 34 to 456.1 over the course of the ten trials.

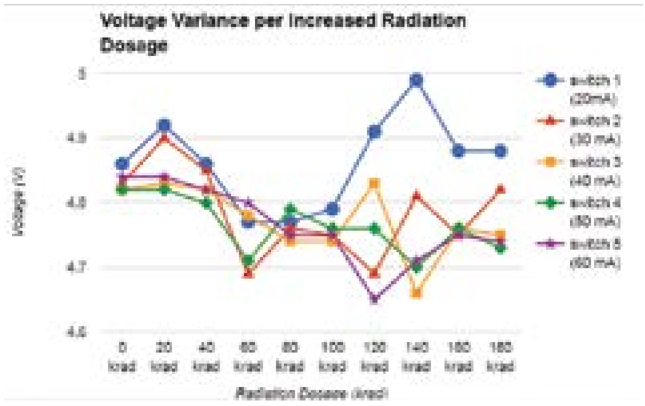

**Figure 2 (a)** The degradation of the ability of the linear regulator to control the output voltage due to radiation exposure.

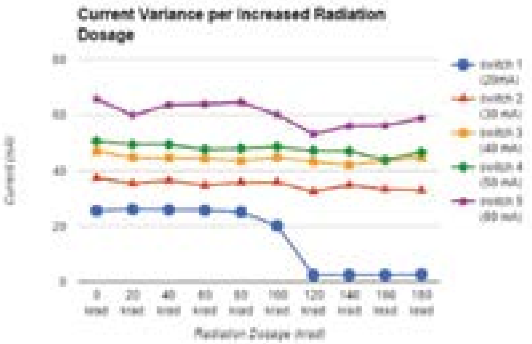

**Figure 2(b).** The fluctuation of the current as a result to the degradation of the functionality of the component.

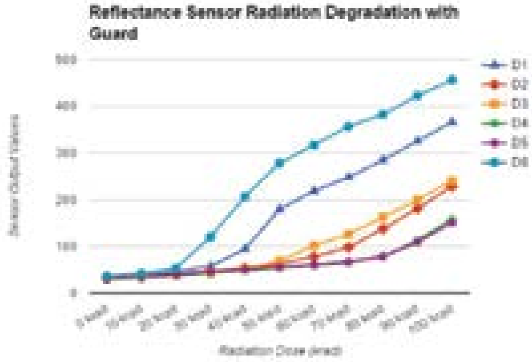

**Figure 3.** The degradation of the reflectance sensor as the radiation dosage increased from 0 krad to 100 krad resulting in tripled and quadrupled sensor output values.

A second failure mode of the reflectance sensor includes false negative, in which the outputs resemble values that are attributed to lighter surfaces. Testing the reflectance sensor over a black sensor with a decreasing input voltage displayed an almost linear correlation between the two factors. Figure 4 shows that a negative correlation exists between the sensor output values decreasing as the input voltage reciprocated.

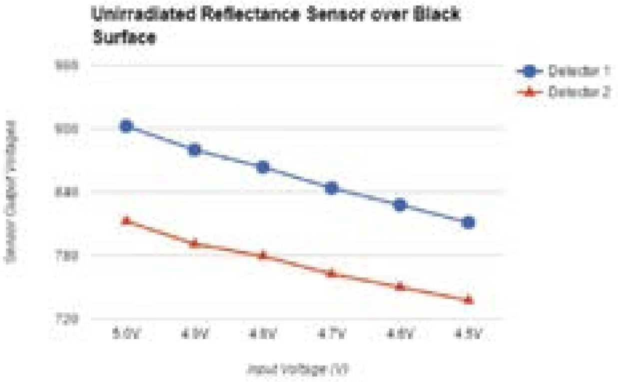

**Figure 4.** The negative correlation between the sensor output values and the input voltage can be seen here through the results of the unirradiated reflectance sensor.

Using the data collected from this research an initial Bayesian Network model was created and is based on previous work[1]. Figure 5 shows the comparison of experimental data to the calibrated BN model. The BN predicts that the response from the reflectance sensor will continue to increase as was observed in Figure 3, while the voltage regulator will steadily decrease until failure of the component is reached as seen in Figure 2a.

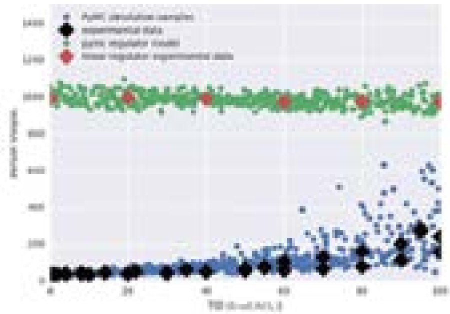

**Figure 5.** The graph created using an early phase of the Bayesian Network Model that predicts the behavior of both components in response to one another as well as to increasing radiation.

## DISCUSSION.

The linear regulator experienced the largest amount of degradation between 60 krad and 100 krad. This provides a guideline on when to begin expecting fault mode behavior from the linear regulator. At 140 krad for the 20 mA resistive load the voltage was found to peak at 4.99V before declining to 4.88V. The erratic behavior of the output voltage at this load was a result of the linear regulator's current reducing to 2.44 mA. The output current and voltage were physical results of the system failure. They were characterized as symptoms of the level degradation of the device from the increasing radiation doses.

Results from the reflectance sensor proved that the physical location of the phototransistor detectors have an effect on how the light is reflected and measured by the sensor. The reduced light to the sensor results in higher values that are associated with darker surfaces. Sensors located at the physical edges show degradation between 20 krad and 30 and deviate from the response of the inner sensors.

## CONCLUSION.

Analysis of the false negative failure mode in the reflectance sensor over the black surface with the decreasing input voltages predicted that the resulting values will decrease almost linearly as the linear regulator degrades. The development and progression of the Bayesian Network Model for these two components showed that there is an indeed inverse relationship between the behaviors of both components and how they will affect each other if degraded simultaneously. The degradation of the linear regulator will cause the reflectance sensor to measure increasingly higher values. Being able to visually see a representation of the future behavior of the components fulfilled a major goal in this research.

The testing conducted in this research needs to be repeated multiple times to quantify the variability in the components' responses and to gain more knowledge of the trends in their radiation responses in order to calibrate the Bayesian Network model. Further concentration and focus on this aspect of the research is priority to forming a practical method of determining component radiation fault modes. With this system, engineers will be able to thoroughly assess when the robotic system will no longer be able to function under extended exposure to radiation environments. This saves money by being able to help prevent robots from being lost in radioactive areas because they cannot be brought back out after malfunctioning and failing. The use of the Bayesian Network Model will allow this research to become a template as to how other engineers can efficiently run performance tests on their robots by doing so under the actual conditions that the robots will be enduring.

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## REFERENCES.

1. T.P. Ma, Paul V. Dressendorfer, Ionizing Radiation Effects in MOS Devices And Circuits, Canada: John Wiley & Sons Inc., 1989, pp. 256. [Online]. Available: https://books.google.com/books? [April 15, 2015].
2. Zachary Diggins et al, "System Health Awareness in Total-Ionizing Dose Environments," *IEEE Transactions on Nuclear Science,* [May 18, 2015].
3. Andrew T. Kelly, et al, "Total Dose in Single Event Transients in Linear Voltage Regulators," *IEEE Transactions on Nuclear Science,* vol. 54, pp. 1327-1334. August 2007.
4. R. Ladbury, J. L. Gorelick, S.S. McClure, "Statistical Model Selection for TID Hardness Assurance," *IEEE Transactions on Nuclear Science,* vol. 56, no. 6, pp. 3354-3360, December 2011.

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