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Research Article

A Performance Evaluation of a Notebook PC under a High Dose-Rate Gamma Ray Irradiation Test

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We describe the performance of a notebook PC under a high dose-rate gamma ray irradiation test. A notebook PC, which is small and light weight, is generally used as the control unit of a robot system and loaded onto the robot body. Using TEPCO's CAMS (containment atmospheric monitoring system) data, the gamma ray dose rate before and after a hydrogen explosion in reactor units 1–3 of the Fukushima nuclear power plant was more than 150 Gy/h. To use a notebook PC as the control unit of a robot system entering a reactor building to mitigate the severe accident situation of a nuclear power plant, the performance of the notebook PC under such intense gamma-irradiation fields should be evaluated. Under a similar dose-rate (150 Gy/h) gamma ray environment, the performances of different notebook PCs were evaluated. In addition, a simple method for a performance evaluation of a notebook PC under a high dose-rate gamma ray irradiation test is proposed. Three notebook PCs were tested to verify the method proposed in this paper.

1. Introduction

After the criticality accident at the JCO uranium refinery in 1999, Japan developed a number of robot systems for emergency response to accidents at nuclear facilities including nuclear power plants [1–4]. In the nuclear robot system for emergency preparedness developed after the JCO criticality accident in 1999, the radiation-hardness design life (20 Gy total irradiation dose) of the robot control unit including electronic circuits, devices, and Toughbook notebook PC was determined assuming that the robot should work for two hours in 10 Gy/h gamma ray dose-rate environments [5]. TEPCO (Tokyo Electric Power Company) improved a Quince robot for responding to underground facility disasters, developed by the Chiba Institute of Technology and Tohoku University, and used it in the accident at the Fukushima Daiichi nuclear power plant [6]. The radiation resistance of the commercial electronic parts used in the Quince robot was evaluated through a gamma ray irradiation experiment using a Co-60 gamma ray source on April 15 and April 20, 2011. A 200 Gy TID (for 10 hours at a 20 Gy/h dose rate) was irradiated onto the CPU board and camera. The experimental results showed that the camera failed at over a 169 Gy cumulative irradiation dose, while the CPU board worked normally [7]. During the accident at the Fukushima Daiichi nuclear power plant, the gamma ray dose rate before and after the nuclear reactor core meltdown, followed by a hydrogen explosion in units 1 and 3 reactor buildings, was more than 150 Sv/h [8]. The ultimate objective of nuclear power plant safety is to prevent the release of radioactive material into the environment. To achieve this objective, a robot system for emergency preparedness in a nuclear power plant should enter the reactor building and PCV (primary containment vessel) and carry out missions to manipulate vent valve operations for the discharge of radioactive gas through a stack. In the stack, a filtration unit is installed to remove radionuclides so that the release of radioactive material into the atmospheric environment can be prevented. Therefore, assuming that a robot system enters the reactor building to prevent or mitigate a severe accident in a nuclear power plant, the robot system should be able to manipulate the components for supplying water inside the reactor area to cool down the decay heat of the reactor core and the valves (open or close) for gas (or steam) discharge in a gamma ray dose-rate environment of more than 150 Sv/h. This means that the robot control unit (notebook PC) composed of semiconductor typed electronic devices, which are embedded in the main body of the robot system, can be operated reliably in a high radiation environment of more than a 150 Sv/h gamma ray dose rate.

In this paper, we describe the performance of a notebook PC under a high dose-rate gamma ray irradiation test. Under the 150 Gy/h gamma ray dose-rate irradiation environments, the performances of notebook PCs are evaluated using an online method. In addition, a simple method for a performance evaluation of a notebook PC under high dose-rate gamma ray irradiation test is proposed. The method uses an abrupt change in the speckle distribution owing to gamma ray irradiation. A notebook PC under high dose-rate gamma ray irradiation test is placed at the target distance from the Co-60 (gamma ray) source. A pilot application program for checking the status of the notebook PC under gamma ray irradiation testing is executed on the same notebook PC under test. The menus of the pilot application programs are then displayed on the LCD screen of the PC under test. A CCD (or CMOS) camera is placed relatively far from the gamma ray source, compared to the target distance of the notebook PC under test. By monitoring an LCD screen using a CCD camera, positioned far from the notebook PC under a gamma ray irradiation test, we can observe the status of the pilot application program (i.e., the operation status of the notebook PC). As the monitoring CCD camera is far from the Co-60 gamma ray source compared to the notebook PC under testing, the intensity of the gamma ray, irradiated onto the monitoring CCD camera, is weak. However, speckles from gamma ray irradiation appeared in the monitoring CCD camera image. When there was no change in the background (gamma ray irradiation facility) during the gamma ray irradiation test, the speckle distribution appearing in the monitoring camera image was uniform. A uniform speckle distribution means that the test sample (notebook PC) is exposed to a constant radiation dose rate. As the irradiation time is increased, the cumulative radiation exposure dose in the notebook PC is also increased. The status of the pilot application program changes abruptly when the totally irradiated dose of the notebook PC exceeds the radiation-hardened dose level of the notebook PC. In this case, the menu of the pilot application program disappears from the LCD screen of the notebook PC, or the menu of an unexpected application program appears, thereby causing an abrupt change in the speckle distribution. By detecting this change in the speckle distribution, it is possible to easily discriminate a performance degradation of the notebook PC under a high dose-rate gamma ray irradiation test.

2. Gamma Ray Dose Rate before and after Hydrogen Explosion

Owing to the SBO (station blackout, i.e., complete loss of AC power in the power plant) caused by an earthquake and tsunami, reactor units 1–3 at the Fukushima Daiichi nuclear power plant lost their emergency core cooling function. In the case of unit 1 reactor, even the instrumentation system did not work owing to the inundation of the DC power source supplied by the backup batteries. According to CAMS (containment atmospheric monitoring system) data of the PCV D/W (dry well) region in unit 1 reactor, which was announced by TEPCO, the gamma ray dose rate was 164 Sv/h on March 14, 06:00, at which time more than one day had passed since the hydrogen explosion on March 12, 15:36. In the case of unit 2 reactor, the maximum dose rate was 138 Sv/h in the CAMS D/W channel at the time of the meltdown, which was followed by PCV damage. In the case of unit 3 reactor, the maximum dose rate was 167 Sv/h before the hydrogen explosion (March 14, 11:01) and 154 Sv/h after it. Figure 1 shows the gamma ray dose-rate distribution of the PCV D/W region of unit 3 reactor. The x-axis in Figure 1 represents about one month of measurement time, from before the hydrogen explosion to when the Packbot robot entered unit 3 reactor building for the first time (April 17, 11:30). The measurement time interval was one hour, on average. The y-axis represents the gamma ray dose rate. Unit 3 reactor experienced a hydrogen explosion around March 14, 2011, at 11:01, and the gamma ray dose rate in CAMS D/W channel A at the time immediately before the explosion (March 14, 10:55) was 154 Sv/h. No measurement data were provided for more than four days, owing to the impact of the hydrogen explosion. In addition, the gamma ray dose rate in CAMS D/W channel A at the time of the Packbot robot entry was 15.9 Sv/h.

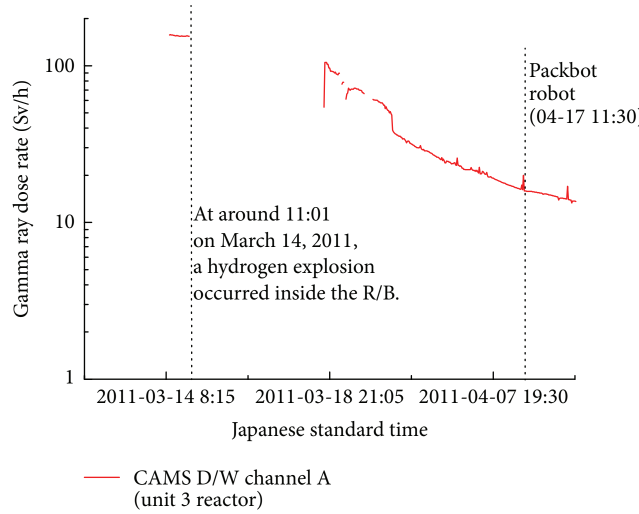


Figure 1: Gamma ray dose rates of the PCV D/W area in unit 3 reactor.

Figure 1 shows the gamma ray dose-rate distribution in the atmosphere between the exterior wall of the RPV (reactor pressure vessel) and the inner wall of the PCV. Since the Packbot robot system entered an area between the exterior wall of the PCV and the inner wall of the reactor building (R/B), it carried out its mission in a much lower dose-rate environment than that of the measured value in the CAMS D/W channel.

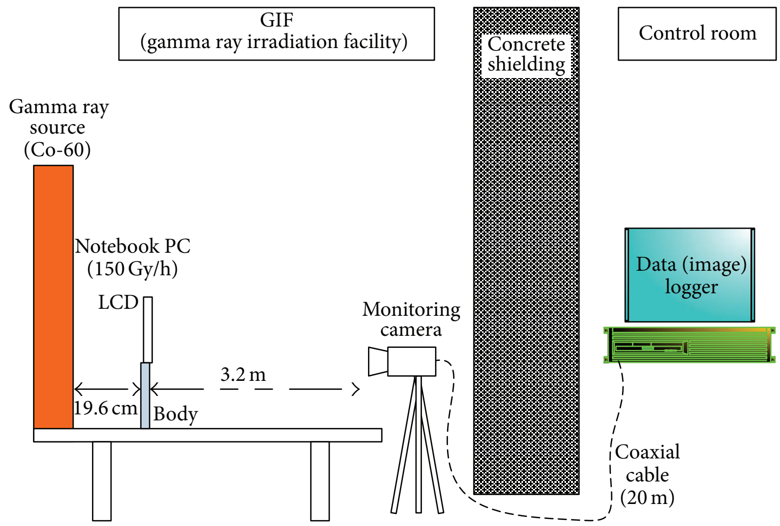


Figure 2: Schematic diagram for gamma ray irradiation test of the notebook PC.

3. Experiments

Figures 2 and 3 show the experimental setup. The notebook PC under test was gamma ray irradiated at a dose rate of 150 Gv/h (19.6 cm distance from Co-60 gamma ray source) until failure. A pilot application program to check the abnormal status of the notebook PC owing to the cumulative gamma ray irradiation dose was executed. A RS-232C loopback test program was executed as the pilot application program, and the menu of the pilot application program was displayed on the LCD screen of the notebook PC under the gamma ray irradiation test. Then, using another monitoring CCD camera, installed at a 340 cm distance (2.11 Gy/h) from the radiation source (Co-60), the LCD screen of the notebook PC under test was observed online. We adjusted the field of view of the monitoring CCD camera such that the LCD screen of the notebook PC under gamma ray irradiation testing was shown fully on the image plane of the monitoring CCD camera. The distance of the monitoring CCD camera from the Co-60 source was determined to be relatively long compared to the notebook PC under test because the camera should robustly observe the status of the pilot application program until the notebook PC under the gamma ray irradiation test failed. As shown in Figures 2 and 3, the main body of the notebook PC under test is nearer to the Co-60 gamma ray source than the LCD screen of the notebook PC under test. Thus, the intensity of the gamma ray dose-rate irradiated at the main body of the notebook PC under test is greater than the LCD screen of the same notebook PC under test. Assuming that the ASIC FPGA, CPU, DSP, and electronic devices, which are generally used in the LCD driver unit and main body of the notebook PC, are made through the CMOS fabrication process, we can estimate that the main body of the notebook PC will fail to function prior to the LCD screen of the same PC as the gamma ray irradiation time elapsed. To discriminate an accurate malfunction point of the notebook PC under a gamma ray irradiation test, the time log is marked on the upper position of the image plane of the monitoring camera. In addition, the observation image of the LCD screen of the notebook PC under testing was periodically recorded on the hard disk of the data logger system (notebook PC), placed in the control room as shown in Figure 2. A USB-2-RS232C conversion module for the RS-232C loopback test is placed behind the lead block (50 × 100 × 200 mm), as shown in Figure 3. As the thickness of the lead block is 50 mm, the intensity of the gamma ray dose-rate irradiated at the USB-2-RS232C conversion module is reduced by less than 1/10. The TVT (tenth value thickness) of the lead material for the Co-60 gamma ray source is 40 mm [9]. The TVT is the thickness of material required to reduce the gamma radiation to one-tenth the intensity. As the cumulative gamma ray irradiation dose increases, the status of the pilot application program of the notebook PC under gamma ray irradiation test is estimated to change. When the notebook PC is under a normal status, the menu screen of the pilot application program does not change. Therefore, speckles appearing in the image of the monitoring CCD camera show a uniform distribution. When the notebook PC is over irradiated beyond the endurance limit of the cumulative gamma ray dose, a subtle change in the menu screen of the pilot application program of the notebook PC under test occurs. By detecting this, the abnormality of the notebook PC owing to a cumulative gamma ray dose beyond the endurance limit can be identified.

4. Results and Discussion

Figure 4 shows the menu screen of the pilot application program executed in the notebook PC under test before the gamma ray irradiation. Figure 5 shows the menu screen of the pilot application program (RS-232C loopback test) of the notebook PC under test during the gamma ray irradiation. The unique difference between Figures 4 and 5 is the speckles. Before the gamma ray source (Co-60) is placed at its irradiation point, the menu of the pilot application program is only observed in the monitoring CCD camera image, as shown in Figure 4. After the source is uploaded to its irradiation position, speckles from the gamma ray are

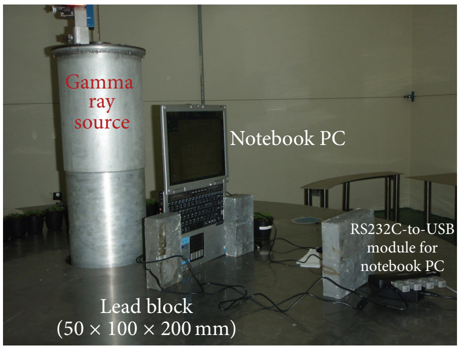


Figure 3: Experimental setup for the notebook PC under a high dose-rate gamma ray irradiation test.

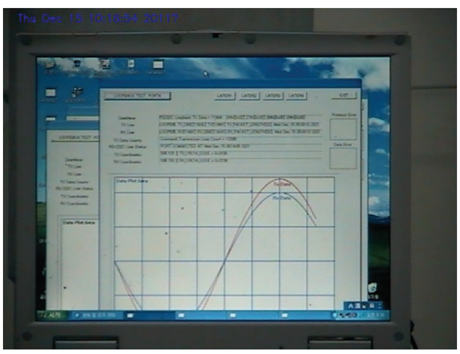


Figure 4: Menu image of the pilot application program, executed on a notebook PC under test (before gamma ray irradiation).

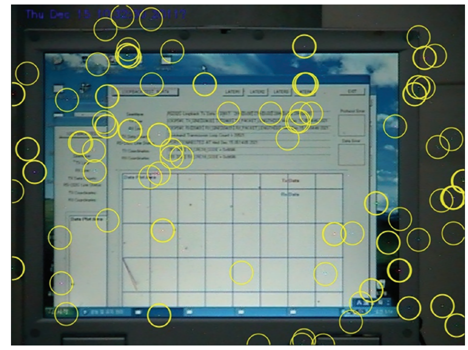


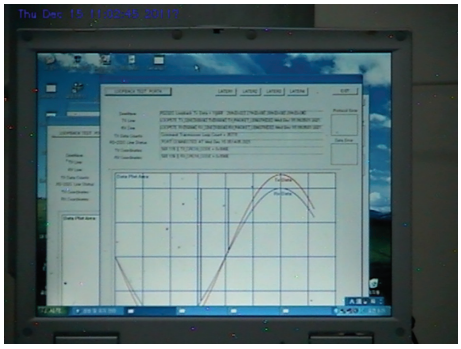
Figure 5: Menu image of the pilot application program, executed on a notebook PC under test (during gamma ray irradiation, about 15 min elapsed).

superimposed onto the image of the monitoring camera, as shown in Figure 5. In Figure 5, the white dots in the yellow circles are speckles.

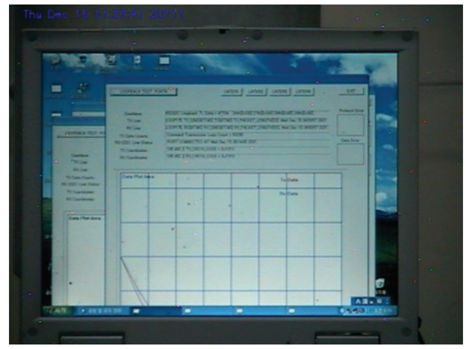
Figure 6 shows the failure of the pilot application program observed at a time when the cumulative gamma ray irradiation dose of the notebook PC under test was about 225 Gy (150 Gy/h × 1.5 h). Figure 6(a) shows the menu of the pilot application program when the notebook PC under test is in a normal state during the high dose-rate gamma ray irradiation. In Figure 6(a), the red (TX) and blue (RX) curves shown in the menu of the pilot application program (RS-232C loopback test) of the notebook PC under test represent the status of the data transmission experiment during the high dose-rate gamma ray irradiation test. If a data transmission error occurs, the peak is drawn in the received waveform (blue curve) at the time of error occurrence, as shown in Figure 6(a). This means that the notebook PC under a high dose-rate gamma ray irradiation test is operating normally. Figures 6(b) and 6(c) show images immediately before and after the malfunction of the notebook PC under test. After approximately 81 minutes elapsed, the LCD screen of the notebook PC under test was abruptly changed. As shown in Figures 6(c) and 6(d), the LCD screen of the notebook PC under test blacked out.

To discriminate whether the failure (phenomena of the LCD screen blackout) of the notebook PC under test was caused by the LCD driver unit or the main body of the same PC, an extended test of the postirradiated notebook PC was conducted for 24 hours in a laboratory (room temperature environment) similar to a control room environment after the gamma ray irradiation experiment was over. Thus, test programs were executed again for 24 hours in the postirradiated notebook PC. In this test, we continuously monitored the LCD screen of the postirradiated notebook PC. Until the initial 4 hours approximately, the notebook PC was normally operated as shown in Figure 7(a). After that, there were abrupt changes in the menu screen of the initial setup of the postirradiated notebook PC (shown in Figure 7(b)), and the windows of various unintended application programs appeared and disappeared repetitively from the LCD screen of the notebook PC, as shown in Figures 7(b), 7(c), and 7(d). From such observation, we could convince that there was no problem in the LCD driver unit and some functions related with LCD display were not working properly in the main body of the notebook PC during the gamma ray irradiation test.

Gamma ray energy is emitted through a nuclear decay reaction of C0-60. If a CCD camera is exposed to a high-energy gamma ray, white noises (speckles) are generated in the CCD camera image sensor. Since the decay of the Co-60 gamma ray source occurs randomly, speckles in the image of the CCD camera, exposed by the high-energy gamma ray source, appeared randomly frame by frame. It can be assumed that the pixel positions of the speckles in the image plane of the CCD camera, generated from the gamma ray irradiation, are also different frame by frame. Although the speckle distribution shown in the two-dimensional CCD image sensor plane is similar, the speckles appearing at certain pixel coordinates of the current image frame of the CCD camera are hardly generated at the same pixel coordinates of the next image frame of the CCD camera. The half-life of the Co-60 radiation source is approximately more than five years. A characteristic of gamma ray energy emitted from the Co-60 source does not change during an approximately two-hour irradiation period. Therefore, we can calculate the number of speckles in the image plane of the monitoring CCD camera, generated from gamma ray irradiation. Speckles from gamma rays are shown well in Figures 6(c) and 6(d). In this paper, the number of speckles generated from gamma rays was



(a) During irradiation (11:02:45, 46 min elapsed)

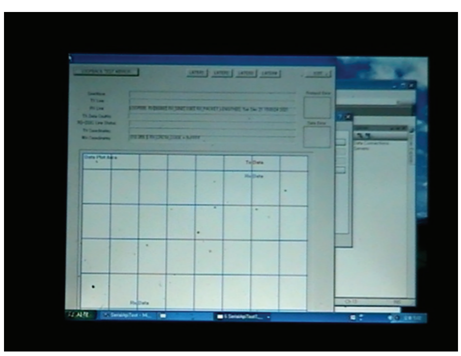


(b) Immediately before malfunction (11:37:41)

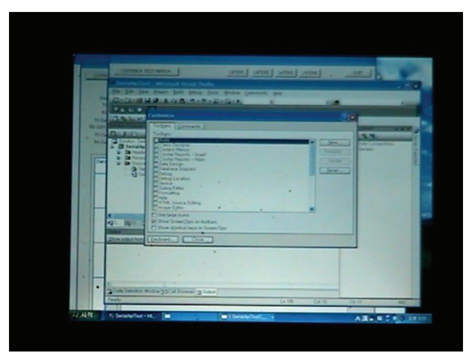
(c) Immediately after malfunction (11:37:42)

(d) After malfunction (11:38:02, 42)

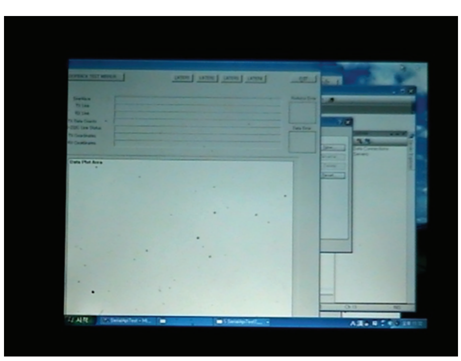
Figure 6: Menu images of the pilot application program, executed on a notebook PC under a high dose-rate gamma ray irradiation test.



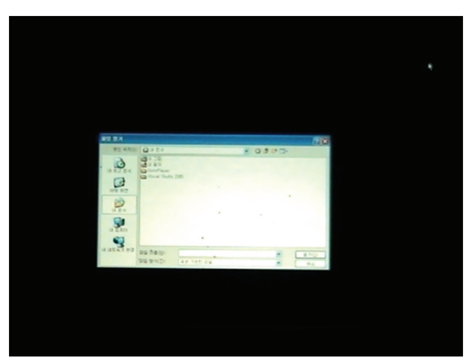
(a) Initial menu on the LCD screen



(b) LCD screen after 4 hours elapsed



(c) LCD menu after 6.5 hours elapsed



(d) LCD screen after 9 hours elapsed

Figure 7: LCD screen changes of the postirradiated notebook PC during the annealing test after gamma ray irradiation experiment.

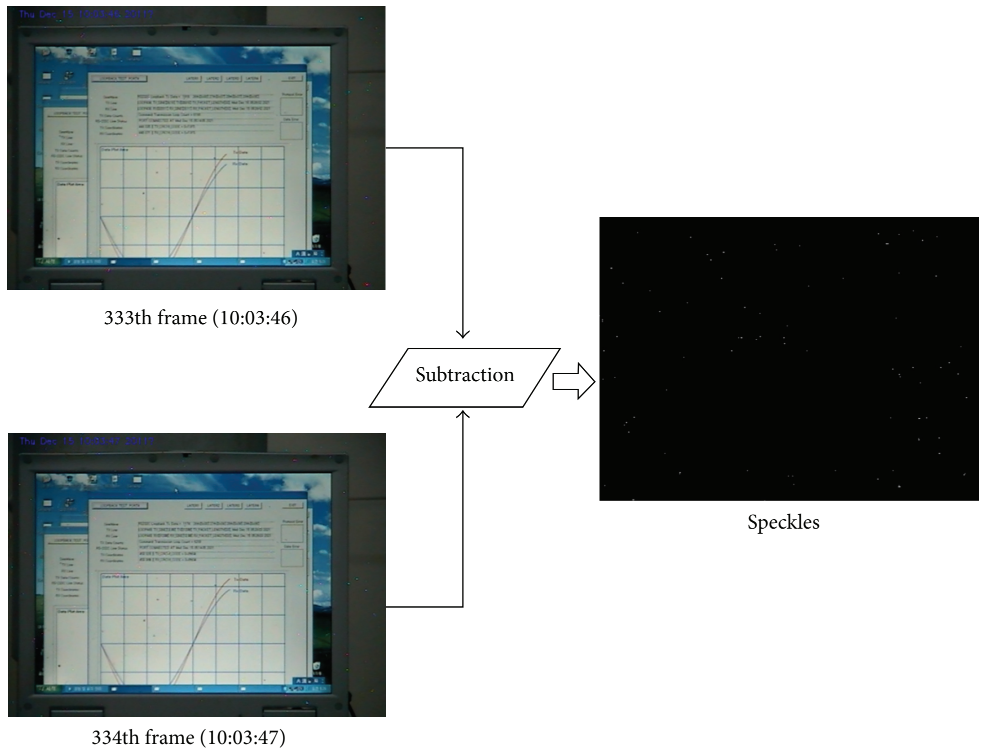


Figure 8: Speckle extraction using an image subtraction algorithm.

calculated through an image processing technique. Since the notebook PC under the gamma ray irradiation test and the monitoring CCD camera were placed at a fixed position in the gamma ray irradiation facility and the surrounding environments (background) are not changed, speckle components generated from the gamma rays can be extracted simply using a background subtraction method. The number of speckles is calculated by (1) and (2):

$$\Delta I_n = I_n - I_{n-1}, \quad (1)$$

where ΔI_n is a differential image and I_n and I_{n-1} are the nth and $n-1$th image frame, respectively. The number of speckles is extracted using the image subtraction algorithm of the previous ($n-1$th) image frame from the current (nth) image frame. $G_{i,j}$ is a gray level at the (i, j) position in the differential image ΔI_n. And $G_{\text{threshold}}$ is a threshold value to remove noises in the ΔI_n image. $S_{i,j}$ is a speckle at the (i, j) coordinates in the differential image ΔI_n. Consider

$$\begin{aligned} \Delta I_{n\,\text{Speckles total counts}} &= \sum_{i=1}^{n}\sum_{j=1}^{m} S_{ij}, \\ S_{ij} &= 1, \quad \text{if } G_{ij} \geq G_{\text{threshold}}, \\ S_{ij} &= 0, \quad \text{else } G_{ij} < G_{\text{threshold}}. \end{aligned} \quad (2)$$

Figure 8 shows the speckle extraction procedure using (1) and (2). As shown in Figure 8, speckles in the graphed region of the pilot application program are hidden by the white component of the drawing area.

Figure 9 shows the speckle distribution calculated from the images of the monitoring CCD camera, which observed

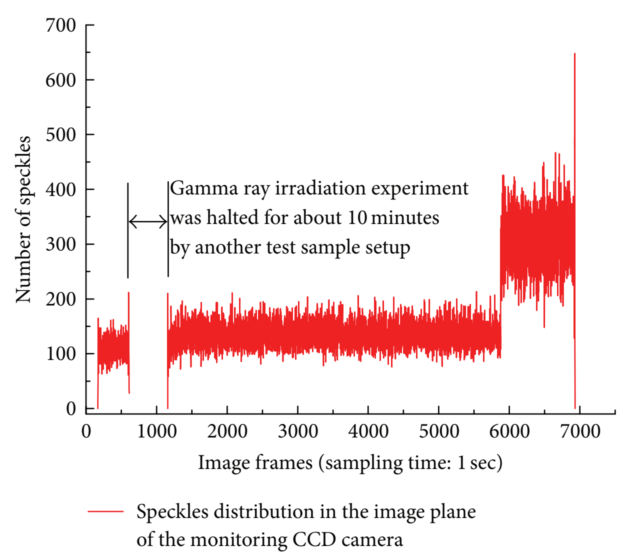


Figure 9: Speckles distribution of the CCD monitoring camera images.

and recorded the LCD screen of the notebook PC under the high dose-rate gamma ray irradiation test.

In Figure 9, the numbers in the x-axis represent the numbers of image frames, stored at one-second intervals during the gamma ray irradiation period; that is, the x-axis is the irradiation time (frame numbers × sampling time). The y-axis shows the number of speckles calculated using (1) and (2). In Figure 9, the number of speckles up to approximately the 5,878th frame was around 130 on average; the number of speckles after that frame was around 300. From this result, it can be seen that the reliable performance of the notebook PC under a high dose-rate gamma ray irradiation test was degraded after the 5,878th frame, which was the time when a change in the speckle distribution occurred abruptly from the normal status, as shown in Figure 6(b), to an abnormal (blackout of menu screen) status, as shown in Figure 6(c). Since the menu screen of the pilot application program of the notebook PC under gamma ray irradiation test had a white background, as shown in Figures 6(a) and 6(b), speckles (white components) generated by the gamma rays were not unveiled well under the condition of the bright white background. The reason for the subsequent high distribution of speckles after the 5,878th frame was because the FOV background of the monitoring CCD camera was changed owing to the blackout of the menu screen of the pilot application program of the notebook PC under the gamma ray irradiation test. Since the background screen of the application program for the online test of the notebook PC was white before failure, speckles (white components) generated in the image of the monitoring CCD camera from the gamma rays were veiled in the bright white background screen and therefore showed a small distribution. Then, after failure of the notebook PC, the menu screen of the pilot application program was blacked out, and the background screen was darkened; speckles (white components) generated in the image of the monitoring CCD camera due to the gamma rays were well unveiled in the dark background screen and thereby showed a relatively high distribution. The limiting conditions (cumulative irradiation dose) for normal operation of the notebook PC under high dose-rate (150 Gy/h) gamma ray environments can be obtained, assuming that the image frame number that showed abrupt changes in the speckle distribution was 5,878, as shown below:

$$\mathrm{TID}_{\text{dose limit of notebook PC}} = \frac{(612 - 166) + (5{,}878 - 1{,}157)}{3{,}600}\ (\mathrm{h}) \times 150\ (\mathrm{Gy/h}) \cong 215\ \mathrm{Gy}. \tag{3}$$

In (3), 612 is the image frame number when the Co-60 source returns to its shelter, and 166 is the image frame number of the monitoring camera when the gamma ray irradiation experiment starts. The time span for first gamma ray irradiation experiment is 446 seconds. And the elapsed time for 2nd gamma ray irradiation experiment is about 1.3 hours. Table 1 shows comparisons of the notebook PCs under high dose-rate gamma ray irradiation testing.

In the case of the 2nd sample, although the menu of the pilot application program disappeared from the LCD screen of the notebook PC under testing, the core function of the pilot application program worked normally for 134 minutes until the cumulative gamma ray irradiation dose reached 337 Gy (150 Gy/h × 134 min/60 min). The notebook PC (3rd sample) under a high dose-rate gamma ray irradiation testing survived for 110 minutes. After 94 minutes had elapsed, the menu of the pilot application program (image acquisition program) disappeared by an unexpected interruption. It is estimated that the memory (DRAM) module of the notebook PC malfunctioned from an overdose of gamma rays. Thus, 94 minutes is considered a robust operation time when assuming that the notebook PC (3rd sample) would be used as the control unit of a robot system.

Table 1: Performance evaluation results of the notebook PCs under high dose-rate gamma ray irradiation test.

Test samples (notebook PC)	Dose rate (Gy/h)	Pilot application program	TID at simple failure*1	TID at irrecoverable failure*2
1 (IWORKS)	150	RS-232C loopback test program	215 Gy	312 Gy
2 (SENS P30)	150	Image acquisition program	247 Gy	337 Gy
3 (X NOTE)	150	Image acquisition program	235 Gy	275 Gy

*1The menu of the pilot application program disappeared from the LCD screen of the notebook PC under test, but the core function of the pilot application program had been normally operated until the irrecoverable dose; *2the startup of the notebook PC was unavailable after irrecoverable dose.

5. Conclusions

In this paper, a method for detecting an abnormal status of notebook PCs, resulting from a cumulative gamma ray irradiation dose, was proposed. The method uses the transient of a speckle distribution appearing in the CCD image owing to the gamma ray irradiation. A notebook PC (test sample) under a gamma ray irradiation survivability test is placed at a certain distance from the gamma ray source. A CCD camera for monitoring the status of the notebook PC under testing is placed at a relatively farther distance, compared to the notebook PC, from the gamma ray source. Then, a pilot application program is executed on the notebook PC under a high dose-rate gamma ray test. A menu of the pilot application program is displayed on the LCD screen of the notebook PC under test. The CCD camera observes the LCD screen of the notebook PC under test. In the monitoring image of the CCD camera, the menu of the pilot application program is viewed including speckles. Speckles appearing in the CCD camera image show that the notebook PC under test is normally gamma ray irradiated. When the notebook PC is overirradiated beyond the endurance limit of the cumulative gamma ray dose, a transient in the menu screen of the pilot application program, executed on the notebook PC under test, occurred. By detecting this using a CCD camera, the abnormality of the notebook PC owing to a cumulative gamma ray irradiation dose beyond the survivability limit could be identified.

In this paper, to calculate the speckle distribution generated in the observation camera from a gamma ray, the background subtraction processing technique was used. The gamma ray dose rate for the notebook PC under test was set at 150 Gy/h by considering the gamma ray dose rate, measured before the hydrogen explosion that occurred in units 1 and 3 reactor buildings of the Fukushima Daiichi nuclear power plant. As the irradiation time increased and the cumulative irradiation dose of the notebook PC under test exceeded the threshold, a transient operation in the menu of the pilot application program, executed on the notebook PC under test, was found. The menu of the pilot application program disappeared, or the menu of the nondemanded application programs appeared on the LCD screen of the notebook PC under test, thereby making changes in the speckle distribution. By detecting this change in speckle distribution, the degradation time from the cumulative gamma ray irradiation dose of the notebook PC under test can be estimated accurately. The experimental results verified that the notebook PC, which can be used as a control unit of a robot controller, operated robustly without malfunctions for about 90 minutes under the 150 Gy/h gamma ray dose-rate environments.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

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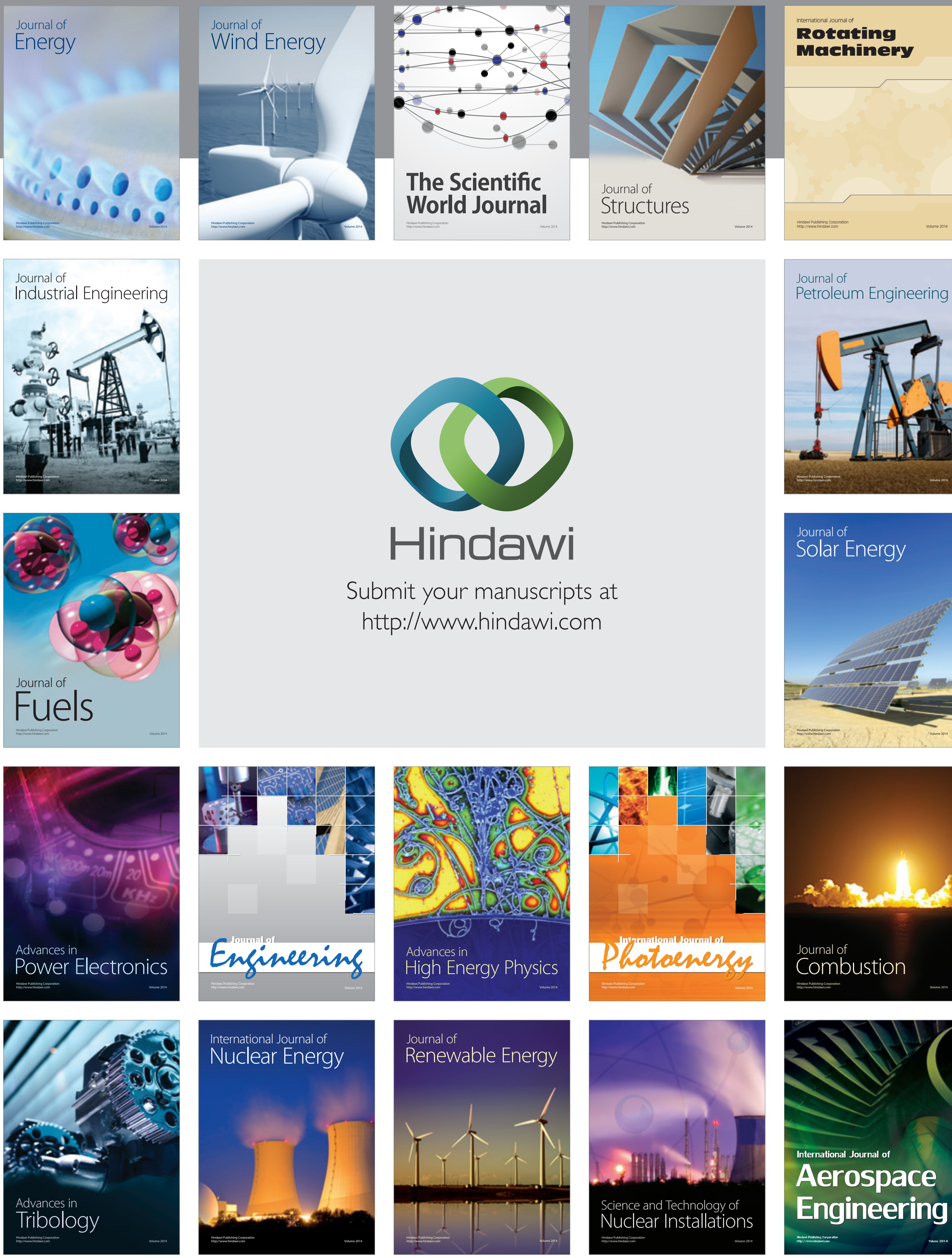
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