

Single event effects evaluation on convolution neural metwork in Xilinx 28 nm system on chip

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Single event effects evaluation on convolution neural network in Xilinx 28 nm system on chip

Xu Zhao(赵旭)[1], Xuecheng Du(杜雪成)[1,†], Xu Xiong(熊旭)[1], Chao Ma(马超)[1], Weitao Yang(杨卫涛)[2], Bo Zheng(郑波)[1], and Chao Zhou(周超)[1]

[1] *School of Nuclear Science and Technology, University of South China, Hengyang* 421001, *China*
[2] *School of Microelectronics, Xidian University, Xi'an* 710071, *China*

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Convolutional neural networks (CNNs) exhibit excellent performance in the areas of image recognition and object detection, which can enhance the intelligence level of spacecraft. However, in aerospace, energetic particles, such as heavy ions, protons, and alpha particles, can induce single event effects (SEEs) that lead CNNs to malfunction and can significantly impact the reliability of a CNN system. In this paper, the MNIST CNN system was constructed based on a 28 nm system-on-chip (SoC), and then an alpha particle irradiation experiment and fault injection were applied to evaluate the SEE of the CNN system. Various types of soft errors in the CNN system have been detected, and the SEE cross sections have been calculated. Furthermore, the mechanisms behind some soft errors have been explained. This research will provide technical support for the design of radiation-resistant artificial intelligence chips.

Keywords: single event effects, convolutional neural networks, alpha particle, system on chip, fault injection

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1. Introduction

Convolutional neural networks (CNNs) have been successfully applied in several fields, such as image processing, object detection, and machine vision, with promising prospects in aerospace.[1–4] The Xilinx Zynq-7020 is an all-programmable system-on-chip (SoC) that features a dual-core ARM Cortex-A9 processor and Xilinx 7-series field programmable gate array. Due to its configurability, design flexibility, and high performance-to-power ratio, this SoC has become a significant application direction for developing the CNN system.[5] However, radiation effects can impact the reliability of electronic systems, leading to a potential malfunction in the performance of a CNN, especially in a space radiation environment, such as single event effect (SEE).[6,7] In this environment, the alpha particle content can reach levels as high as 14%.[8] On the other hand, the alpha particles can originate from both the packaging materials and the nuclear reactions resulting from the interaction of neutrons with boron-doped semiconductor devices.[9] Soft errors induced by alpha particles pose a critical threat to the reliability and operational lifespan of modern electronic systems.[10,11]

Therefore, it is crucial to study SEE induced by alpha particle on CNN systems in order to develop its space applications. In this work, irradiation test and fault injection experiment are performed. The alpha radiation was used to accelerate the SEE process, and the sensitive parts of the CNN system were discovered by fault injection. The soft error mitigation (SEM) intellectual property (IP) core was utilized to perform the fault injection and emulate the single event upset (SEU) in the configuration memory (CRAM) of the CNN system.[12–14] The SEE of the CNN system can be evaluated in a comprehensive way.

Research has been conducted on the reliability issues of a CNN system induced from SEU in CNN parameters and processing elements (PEs).[15] Moreover, attention has been given to the radiation sensitivity of different CNN models, such as failure distributions and mechanisms.[16] Furthermore, the impact of data bit compression or model quantization techniques on the SEE reliability of the CNN system has been evaluated.[17]

In this paper, the CNN-based recognition of handwritten digits in MNIST data set has been implemented in Xilinx Zynq-7020 SoC, and its soft errors have been evaluated by alpha radiation sources and fault injection in CRAM. This paper is organized as follows. Section 2 introduces the CNN architecture and its implementation on Zynq-7020 SoC; Section 3 describes the experimental platform, experimental process, and alpha experimental results; Section 4 details the fault injection processes and shows the fault injection detected results of CNN system; Section 5 compares the results between alpha radiation and fault injection experiments; finally, Section 6 provides a summary of this paper.

2. Design and implementation of CNN accelerator on SoC

2.1. CNN architecture

The CNN architecture comprises a convolutional layer, pooling layer, activation function (ReLU), dropout, fully connected layer, and Softmax,[18] as shown in Fig. 1. The MNIST

†Corresponding author. E-mail: duxuecheng@usc.edu.cn

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data set consists of 28×28 pixels images of handwritten decimal digits from 0 to 9. It is a widely used database that serves as a benchmark data set for CNN training. A data set of 28×28 pixels images of handwritten numbers 0 through 9 is provided to the CNN, making up a total of 784 pixels of input data. The digital image is processed through MNIST CNN model, and eventually the output to a 10-category probability distribution produces numerical classification results.

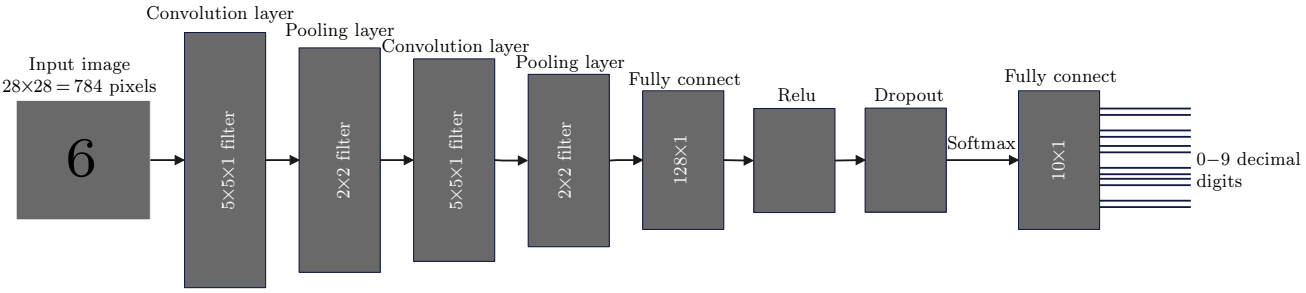


Fig. 1. The CNN architecture.

2.2. CNN system design

The Xilinx Zynq-7020 SoC integrates a dual-core ARM Cortex-A9 based processing system (PS) and programmable logic (PL) component in a single die. The CNN IP core involved designing the conv and pool cores was based on the topology of the network and parameters, with reference to the top of CNN algorithm. The Xilinx High Level Synthesis tool was applied to convert the high-level programming language to hardware description language, which allowed us to derive the conv and pool IP cores.[19] Next, the Vivado software suite was used to connect the processor suite with conv and pool cores. Eventually it loaded the created tool command language (tcl), bitstream files, MNIST data set, and CNN model parameters into the SD card of Zynq-7020 SoC and set the SD card start-up mode. The digital recognition functions of the CNN system have been implemented.

The CNNs involve a large number of multiply-accumulate (MAC) patterns, and the MAC operation is implemented by DSP hardware blocks present on the PL side of the Zynq SoC. The resource utilization of CNN on ZYNQ SoC is shown in Table 1, including look up table (LUT), LUTRAM, flip-flop (FF), block RAM (BRAM), digital signal processor (DSP), and global clock buffer (BUFG).

Table 1. MNIST CNN the proportion of resources.

Resource	Utilization	Available	Load ratio (%)
LUT	8138	53200	15.30
LUTRAM	395	17400	2.27
FF	12147	106400	11.42
BRAM	2	140	1.43
DSP	41	220	18.64
BUFG	1	32	3.13

3. Alpha source experimental setup

3.1. CNN radiation test system

The alpha particle irradiation experiment uses an americium-241 source with a diameter of 35 mm. It emits alpha particles from the surface of the cylindrical source. The emission has an emissivity of 5.32×10^5 particles/2π·min and a thickness of 1 mm in a circle. The majority of the energy released through alpha decay is 5.486 MeV, accounting for 84.87%, while 5.443 MeV for 13.1%, and 5.388 MeV for the remaining 1.66%.[20] The relationship between the linear energy transfer (LET) in silicon and the energy of the alpha particle is shown in Fig. 2. The range, LET value, and energy of alpha particles in silicon are produced based on the SRIM-2013-pro software. For the 5.484 MeV alpha particles, the LET value is 0.5758 MeV/mg·cm^{-2} and the range in silicon is 27.9 μm. According to the international standard JESD89 A,[21] it is consequently appropriate for CNN soft error experiment. The SoC chip packaging material should be removed from the surface to ensure that the alpha particles have sufficient energy to reach the sensitive area of the chip.

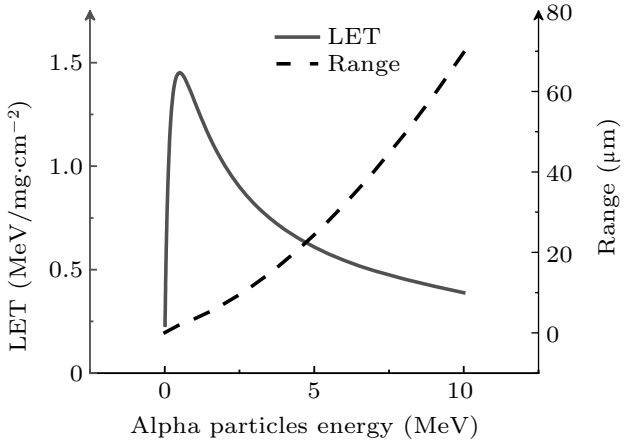


Fig. 2. The LET and range of alpha particles in silicon vary with energy.

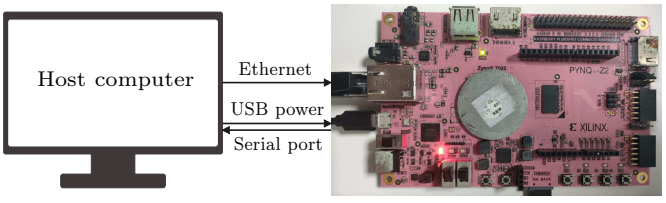


Fig. 3. The system architecture of SoC irradiation experiment.

The experimental system is shown in Fig. 3. The system is composed of the host computer, the SoC test board, and the ^{241}Am alpha source. The upper computer connects to the SoC test board through the USB and Ethernet ports, which supply power and communicate data.

3.2. CNN experiment flow

The process of the irradiation experiment is described in Fig. 4. To construct the MNIST CNN system, it is necessary to conduct the CNN training in order to adjust CNN model parameters, such as weight and bias, to optimal values. The trained model can be used to design a CNN system based on the Xilinx 28 nm Zynq-7020 SoC. During the irradiation experiments, the alpha source is placed on the SoC. If a system error occurs, the SoC test board should be reconfigured. The time of the alpha irradiation experiment and any phenomena are recorded until the number of errors exceeds 100 or the particle flux exceeds 10^7 particles/cm^2.

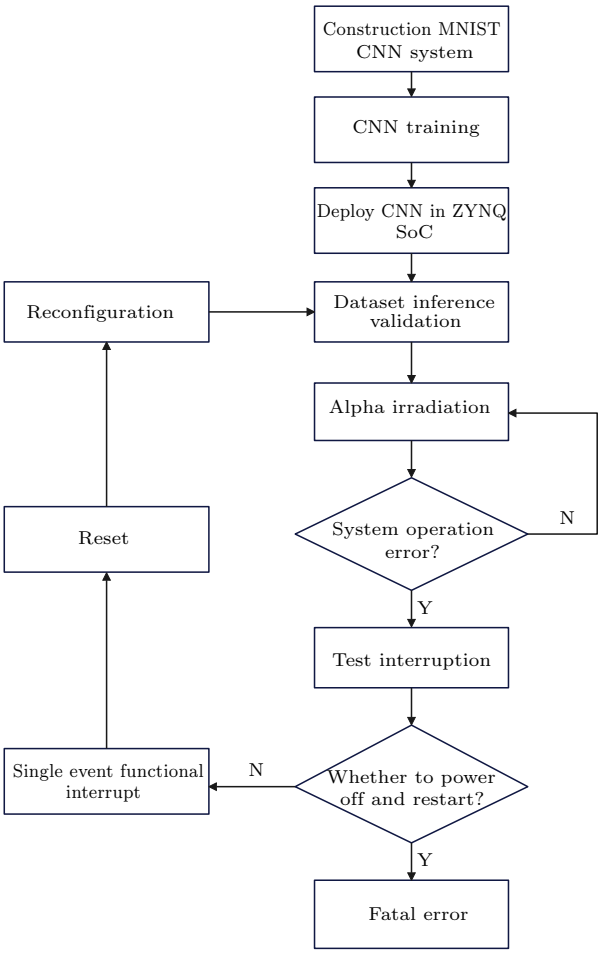


Fig. 4. The test procedure of SoC irradiation experiment.

3.3. Alpha experiment results and analysis

According to the experiment phenomena, the observed soft errors of the CNN system can be categorized into ten types. The following is a description and analysis of the detected soft error caused by the alpha irradiation experiment.

(1) Bus error: When a CPU accesses data, the address must usually be aligned. Bus error occurs when the address is not aligned, causing an access failure and the bus is unable to transfer the data at the corresponding address.

(2) CNN system output hang: The CNN system's output hang (CSOH) is composed of two parts. The first is when reading a data set, the system stops validation after CNN inference validates part of the data set, and the second is CNN program verification hang.

(3) Recognition error: The CNN system interrupts when the CNN system image classification error such as 2 to 3, or repetition identifies numbers in a data set as the same number or two numbers, such as repeats of 0 or 1 and 7. It is worth noting that recognition errors occurred only nine times under alpha source irradiation.

(4) Program corrupt: During the irradiation process, two types of corruption can occur. The first is that a huge number of repeated or non-repetitive garbled codes occur during the SoC system reset or program execution and do not stop automatically, and the second is SoC system corrupts at the import procedure or first stage boot loader stage before reading the data set.

(5) Kernel crash: The driver module accesses the memory address exception while performing the interrupt handler. Once a kernel crash occurs, the driver module is unable to process more system interrupt requests, resulting in a kernel crash.

(6) Repower: In rare situations, the reset is invalid, and thus the SoC can only be turned down and restarted.

(7) Data transfer error: Data transfer error (DTE) can be caused by the incorrect address, memory, UART port, or type in the case of irradiation.

(8) Segmentation error: When the system is reset or the program is starting, the following error occurs: segmentation fault or Seg fault @ (0xb11cce30)10-bit address. This is caused by a memory exception in the SoC system when the CNN system has accessed a memory address but no physical memory corresponds to that address.

(9) Single core error: In an alpha irradiation condition, a soft error occurs: symmetric multiprocessing (SMP): failed to stop secondary CPUs. In other words, a soft error causes a single core of the CPUs in a symmetric multiprocessor system to fail. This indicates that at least one of the CPU's cores on the Zynq SoC's PS and PL sides is not functioning properly.

(10) Kernel tainted: The SoC system shows that

Tainted: GD and accompanied by OOPS and BUG;

G: if all modules loaded have a general public license (GPL) or compatible license;

D: if the kernel has died recently, there was an OOPS or BUG.

This indicates that some oops reports contain the string 'tainted': after the program counter. This also indicates that

the kernel has been tainted by some mechanism. The string is followed by a series of position-sensitive characters, each representing a particular tainted value. The appearance of GD indicates that the system that was loaded did not have a GNU GPL or compatible license and the kernel has died recently.

The SEE cross section can be calculated by[22]

$$\sigma = N/F, \tag{1}$$

where σ is the cross section of SEE in cm^2; N is the number of SEE event; F is the α particle fluence in particles per cm^2. The alpha experiment fluence is 3.98×10^7 particles/cm^{-2}.

Table 2 summarizes the results of the CNN experiment. The soft error events were divided into 10 types and the SEE cross-section data corresponding with the different error types were computed.

Table 2. The soft error experiment results of ZYNQ SOC.

Soft error type	Number	Proportion (%)	Cross section (cm^2)
Bus error	58	20.3	1.46×10^{-6}
CNN system output hang	73	25.5	1.84×10^{-6}
Recognition error	9	3.2	2.26×10^{-7}
Program corrupt	12	4.2	3.02×10^{-7}
Kernel crash	52	18.2	1.31×10^{-6}
Repower	3	1.1	7.54×10^{-8}
Data transfer error	13	4.5	3.27×10^{-7}
Segmentation error	31	10.8	7.79×10^{-7}
Single core error	18	6.3	4.42×10^{-7}
Kernel tainted	17	5.9	4.27×10^{-7}

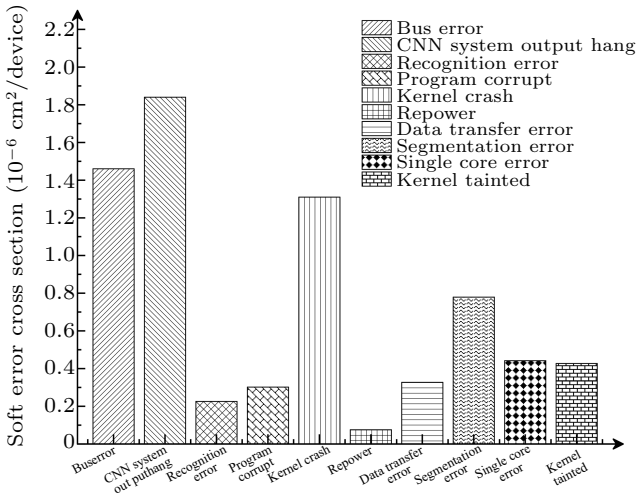


Fig. 5. The SEE cross sections of CNN system.

In the irradiation environment, the CNN system was found to be more susceptible. The SEE cross section of 10 types of sort errors is shown in Fig. 5. The distribution of soft errors is depicted in Fig. 6. Among all the experimental results, the recognition error only accounts for 3.1% of all error types. Compared to the recognition error, the other error types ratios are much higher, which have a serious impact on the reliability of the CNN system.

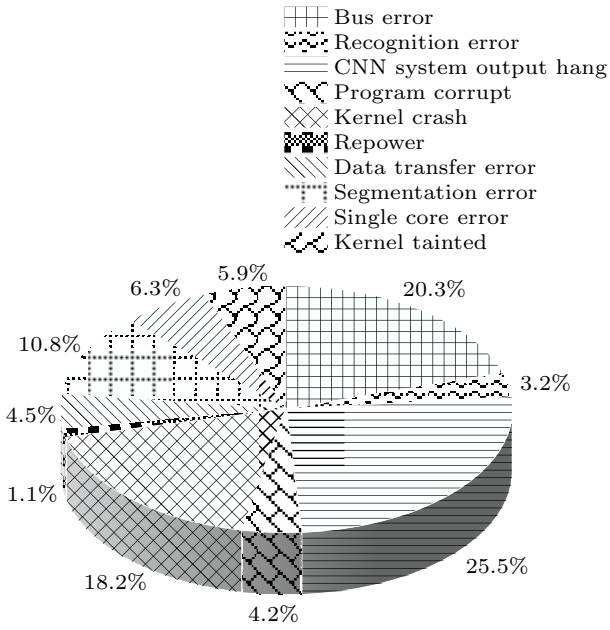


Fig. 6. The distribution of soft errors.

4. Fault injection system based on CNN

4.1. Fault injection design

Fault injection is an effective technique for evaluating the reliability of CNN systems.[23] According to the above alpha irradiation experiment, the CNN system based on SoC has been discovered to be sensitive to these soft errors. A soft error that occurs in the configuration memory of SoC can alter the circuit function, and the error persists until the SoC is reconfigured. The SEU fault injection test platform was developed by using Xilinx SEM IP in Zynq-7020 SoC. The SEM IP is used to emulate the faults in CRAM, and it is also implemented to verify the fault tolerance of the CNN system. For the SEM IP, it has many functions about injection, correction, repair mode, and they can be separately or simultaneously active in a design. The fault injection, error correction and error repair in CRAM were valid in the fault injection platform. Compared to other fault injection methods, fault injection based on SEM IP is highly consistent with the original operation system without any additional hardware. Moreover, the implementation of SEM IP-based FI platforms is a fast and more convenient way to analyze CNN system CRAM reliability.

FI in CRAM can be implemented in many methods, including reconfiguring, modifying, or simulating the CRAM. There are two common ways to perform a fault injection experiment: injecting bits one-by-one and randomly injecting bits. However, injecting one-by-one is very time-consuming in fault injection. There are two ways to perform a random fault injection: randomly inject into all the CRAM or randomly inject the essential bits. It is very important to choose the inject-bit for the random fault injection. Since the essential bits are the bits in the CRAM that are relevant to the current

design,[24,25] the second method is more efficient than the former.

It is worth noting that not at all flipped essential bits can cause CNN system soft errors. The essential bits are related to the EBC and EBD files, which can be produced in the block design generating bitstream process by adding the following property in Vivado: 'set_property bitstream.seu.essentialbits yes [current_design]'. Then, the essential bits data and percentage are generated in the Vivado tool command language (Tcl) console, for example, 'This design has 1930358 essential bits out of 25697632 total (7.51%)'. For the EBC file, its mask file is the EBD file, and it is important to note that in EBD file '1' corresponds to the essential bits in the EBC file. In the EBC and EBD files, the current design's pad words and other descriptive information are included. For the Zynq 7020 SoC, the pad words in the EBC file are 101 words. The complete essential bits of the current design can be extracted based on the correspondence between the EBC and EBD files. The numbers and proportion of CNN system essential bits are listed in Table 3.

Table 3. The numbers and proportion of CNN system essential bits.

All bits	Essential bits	Essential (%)
25697632	1930358	7.51

The 101 words in the EBD file make up a frame in Zynq 7020 SoC. Since the frame is the smallest addressable unit in configuration memory, the essential bits should be transferred to the fault injection linear frame addresses (LFA) frame. The LFA length is 40 bits, and the format is shown in Table 4. To execute the FI efficiently, in this paper randomly extracted 50000 LFA frames are used to verify the reliability of the CNN system.

Table 4. The addressing format of Zynq 7020 SoC fault injection using LFA.

Bit	39-36	35-31	30-29	28-12	11-5	4-0
Meanings	C	0	0	LFA	word address	bit address

The FI framework is shown in Fig. 7. During the fault injection, the LFA address and FI instructions are transferred from AXI UART to SEM IP. The FI system is composed of AXI UART module, UART, SEM IP, and MNIST CNN.

For fault injection in the CNN system, five stages are required: CNN training (adjusting model parameters: weight and bias), design CNN IP core (conv and pool), CNN fault injection system block design (produce essential bits), fault injection script creation (produce LFA frame), load FI injection script and program to SD. The fault injection design flow is presented in Fig. 8. In the block design the system connects the designed MNIST CNN with SEM IP, then produces the EBC and EBD files in Vivado block design, and generates the bitstream. The fault injection script is created as follows: randomly extract a 50000 LFA frame address from the transferred file to achieve an FI script. The data were loaded to the SD card, including inject script and procedure, and then the CRAM fault injection was performed.

The SD card includes the generated 50000 LFA frame address and FI program. The fault is injected one-by-one from the fault injection script by SEM IP's internal configuration access port interface. In repair mode, each injected fault will be repaired. The error results are recorded until 50000 faults are injected.

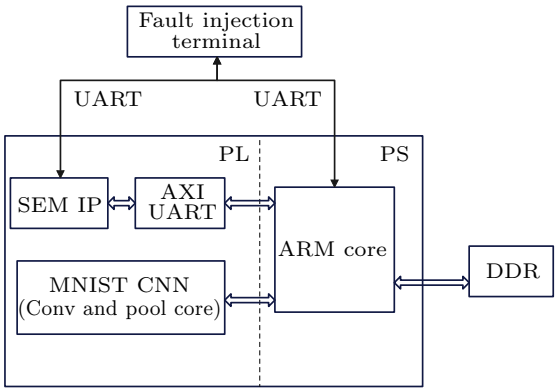


Fig. 7. The CNN system fault injection overall framework.

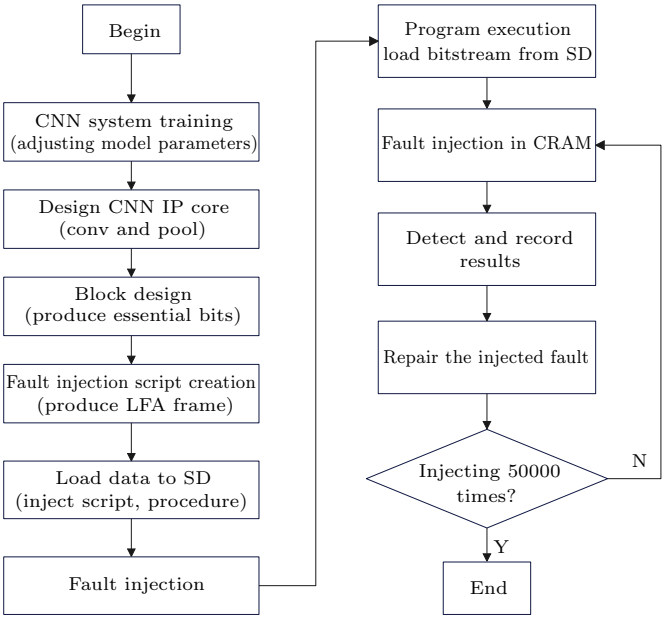


Fig. 8. The CNN system fault injection full flow.

4.2. Fault injection results and analysis

For the CNN system, when one LFA is injected as a fault, the following four kinds of detected results are recorded. For the detected results, they are fault injection system output hang (FISOH), bus error, DTE and corrupt program. These results mean that the injected LFA is sensitive. The number of detected errors from the CNN system is shown in Table 5.

Table 5. The error information.

Injected faults	Detected failure type	Number	All errors	Proportion (%)
50000	fault injection system output hang	307	397	77.3
	bus error	45		11.3
	data transfer error	34		8.6
	program corrupt	11		2.8

Detected errors are as follows: (1) Fault injection system output hang (FISOH). 1. The CNN system does not output any message and a reset is required. 2. The direct memory access command queue is not right. (2) Bus error. The FI system exits after outputting 'bus error'. (3) Data transfer error (DTE). 1. The writing image data to CNN system error. 2. The CNN system cannot read or write the CNN system parameters and FI results. (4) Program corrupt. The CNN system outputs a large number of repetitive or non-repetitive garbled codes.

The detected errors are mainly FISOH. Since the CNN system processes lots of data, when a CRAM bit is flipped, it causes the CNN system output to hang. The FI results show that another important phenomenon is the bus error. When a CRAM bit is flipped, it results in the address not being aligned, causing an access CNN system data failure. For the DTE, a flipped bit in the CRAM leads to an image or CNN system parameters error.

5. Comparing alpha experiment with fault injections

The alpha experiment results indicated that 10 errors can lead to the CNN system exceptions or crashes. The fault injection experiment showed four errors: bus error, FISOH, DTE, and corrupt program. They have also been detected in the alpha experiment. For the system output hang, the alpha experiment and fault injection percentages are 49.3% and 77.3%, which have a serious impact on the reliability of the CNN system. The bus error and DTE can be caused by bit flips in the CRAM. In addition, the CNN system relevant errors are higher than digital classification errors, so the operating system on the PS side was found to be more susceptible to radiation and the CNN operating system should take mitigation measures. Due to alpha irradiation, the SoC processor could not correctly access the data in memory address and register physical address, such as layer information, weight offset address, and weight quantity, which led to CNN system exceptions. For the complexity of the CNN system, there are many more complex failure mechanisms for the soft errors to explore.

6. Conclusion

The impact of SEUs on a CNN system based on 28 nm Xilinx Zynq-7020 SoC has been evaluated using alpha source experimental and SEM IP fault injection. The alpha experiment and fault injection illustrate that SEEs can cause system exceptions. During the alpha irradiation experiment, 10 types of errors have been detected. The SEE cross sections and distribution of different types have been obtained. Moreover, the related mechanisms of four soft errors in the alpha experiment have been analyzed in detail by fault injection technology. The bit flips in CRAM can cause system output hang, bus error and DTE. The research results will provide guidance for the CNN's radiation reinforcement design on the Xilinx 28 nm SoC in the future.

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