A systematic literature reviews of multichannel analyzer based on FPGA for gamma spectroscopy

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Abstract. Environmental radiation monitoring based gamma spectroscopy require a multichannel analyzer (MCA) which functions to record and analyze nuclear radiation spectrum data. There are currently many studies related to MCA based on field programmable gate array (FPGA). But, the scope of these published research is complex and fragmented. This systematic literature review (SLR) main objective to analyze research trends and emerging themes research of MCA based on FPGA for gamma spectroscopy that was developed during last 10 years. This review was conducted by selecting papers from leading journals in scientific databases namely ScienceDirect, IEEE Xplore and Scopus. For papers selection process, specific keyword strings used for each database and paper selecting using inclusion and exclusion criterion. Selection of papers resulted in 38 selected papers. During 10 last 10 years, This research become hot of topic research especially in Asia. This SLR proves that performance of MCA based FPGA is reliable and compatible with various of detector types. This MCA has been used for spectroscopy applications such as monitoring radiation, diagnostic medicine, industrial imaging and security screening. The implications of this study can used as reference for future research of development MCA based FPGA for enviromental radiation monitoring based gamma spectroscopy.

1. Introduction
Multichannel analyzer (MCA) is a main component in Enviromental radiation monitoring based gamma spectroscopy used for measurement and identification of radioactive sources from natural and artificial background radiation. MCA records distribution of the pulse height from particles emitted by radioactive sources detected using detector. Currently development of gamma spectroscopy devices has been using digital MCA. The advantages of digital MCA compared to analog MCA are rapid nuclear spectra analysis speed, higher pulse speed, using programmable devices to digital signal processing [1]. This reason makes digital MCA widely used in nuclear spectrum analysis. Currently many integrated circuit (IC) and software can be used to develop and produce digital MCA. One of the integrated chips used to develop MCA is field programmable gate array (FPGA).

FPGA is an integrated circuit that can be designed to be configured by a programmer to implement digital circuits and perform special functions. Currently FPGA has been becoming a core component such as data acquisition of nuclear spectrum, digital signal processing systems and data communication with a computer. FPGA has parallel computing capabilities, which has made FPGA
become ideal for digital signals processing with high performance [1-3]. Acquisition and digital signal processing systems using FPGA chip also can simplify the hardware design of digital MCA, reducing its power consumption and low cost [1, 4]. This reliability has made many researchers interested using FPGA to develop digital MCA for gamma spectroscopy applications.

Many research datasets related to the development of MCA based FPGA for gamma spectroscopy. The papers published provide design of digital MCA, pulse signal processing, results experiment and application for gamma spectroscopy. But, the scope of these published research is complex and fragmented. So that a comprehensive picture of the current state of MCA based on FPGA research that exists is missing. This systematic literature review (SLR) aims to identify and analyze research trends, emerging themes research and scope for future research of development MCA based on FPGA for enviromental radiation monitoring based gamma spectroscopy. This review was conducted by selecting papers from leading journals in three scientific databases namely ScienceDirect, IEEE Xplore and Scopus from 2010 to 2019.

The writing of this paper is organized as follows. Section 2 present on the research methodology to search the relevant papers for the study. Section 3 presents the results and discussion for answers of research questions. The final section of this paper conclusions.

2. Method

Study literatur related MCA based on FPGA for gamma spectroscopy has been used methode systematic literature review. Guidelines systematic literature review first time proposed by Kitchenham and Charters that identifies, assess, and interprets all findings on a research topic to answer research questions (RQ) [5].

2.1. Research questions

The first stage in this study, We have been define three main research questions as follow :

- RQ 1 : How many studies related this research topic, publication trends, papers distribution, citation analysis and geographical distribution were published during last 10 years?
- RQ 2 : What emerging themes research among papers publications?
- RQ 3 : What main component of spectroscopy device among papers publication?
- RQ 4 : How scope of future research of this topic research for development enviromental radiation monitoring?

2.2. Scientific databases for papers searching

Literatur review was conducted with collect relevant paper on three literature databases, which are ScientDirect, Scopus and IEEE Xplore. We selected only jurnal and proceding conference was published during last 10 years and written in English.

2.3. Study selection of papers

The process of papers selection was performed in many stages as shown in Figure 1. For relevant papers selection, we used the inclusion and exclusion criterion listed in Table 1. Firstly, searching of papers in scientific databases using command search and inclusion criteria. For searching papers in each databases used specific keyword string, as described bellow.

- ScienceDirect : Title, abstract or author-specified keywords (“multichannel analyzer” OR “MCA”) AND (“FPGA”)).
- IEEE Xplore : (“multichannel analyzer” OR “MCA”) AND (“FPGA”) with all meta-data in the command search.
- Scopus : title-abs-key (“multichannel analyzer” OR “MCA”) AND (“FPGA”)).
This stage resulted in total 337 papers for consideration with each contribution database that is (ScienceDirect 132 papers, IEEE Xplore 110 papers, Scopus 95 papers). Second stage removing of papers using exclusion criteria. The next stage, we selected paper based on by title, keywords and abstract, which had a clear focus this topic research. Final stage, we performed full text read to ensure that papers according to the this topic research. Final stage resulted in 38 of selected papers to be a part of this SLR.

![Diagram of papers selection process](image)

**Figure 1.** Papers selection process

| Inclusion criteria                                    | Exclusion criteria                                           |
|-------------------------------------------------------|--------------------------------------------------------------|
| Topic research should focus on MCA based on FPGA     | Paper not related this topic research                        |
| Papers published in three database journal (ScienceDirect, Scopus and IEEE Xplore) | Duplicate papers                                            |
| Papers published from 2010 until 2019                 | Papers published before 2010                                 |
| Papers published written in English                  | Papers published not written in English                      |
| Article type is journal and proceeding conference     | Other article type such as book, encyclopedia, mini reviews and short communications |
|                                                      | Papers without full text (not open acces)                    |

**Table 1.** Inclusion and exclusion criteria

2.4. **Data extraction**

After selection of papers process, We was used software End Note X8 to manage and store selected papers. All data and information are recorded in Microsoft Excel for literature analysis.

3. **Results and discussion of the systematic literature review**

3.1. **Publication trends**

Selection of papers resulted 38 selected papers. Figure 2 show the distribution of papers from 2010 to 2019. During last 10 years, the average of 3.8 papers per year were published. In 2010 only one paper was published. Then start going up from 2011 to 2013 with an average paper that has reached 5 papers per year. In 2014 was the culmination of this research with 9 papers published. But after that, in 2015 and in 2016 come down, and average number of issued papers only 1 paper per year. The last three years this research topic increased again with an average number of papers published is 3.66 papers per year or almost the same as the average papers for 10 years.
Based on publication trends, shows that many researches interested with this topic research during last 10 years. But, the development of this research is relatively stagnant. Main reason is the development and utilization of nuclear technology in the world still limited.

![Figure 2. Distribution of papers per year](image)

3.2. *Publication papers distribution among journals and conferences*

Studies on MCA based on FPGA for gamma spectroscopy have been published in various journals and conferences. From 38 papers selected consisted of 27 papers were published in journals and 11 papers were published in conferences.

Figure 3 is the number of papers published in each journal. The research paper was published in 13 journals. Among 12 journals, journal of Nuclear Instruments and Methods in Physics Research Section A is top journal with 12 publications. Second place is Applied Radiation and Isotopes with 4 publications while other journals only one publication.

![Figure 3. Number of papers published in each journal.](image)
3.3. Geographical distribution of the papers publications

Figure 5 shows a graph of the distribution of publication papers geographically during last 10 years. From this graph shows that Asia is the continent with the most papers published for this research topic with 20 papers or 53% from papers distribution in the worldwide. Second place is Europe continent with 12 papers or 31% of the total papers in the worldwide. The third rank is the North American continent with 6 papers or 16% of the papers in the worldwide. While other continents no publication. This fact shows that the development of research related to nuclear instrumentation especially gamma spectroscopy device in the Asian continent is very high. Data showing that the European continent and the North American continent are fewer papers published due to nuclear instrumentation on the continent is well established. While in other continents such as Africa, Australia and South America there is no publication of this research topic. The main cause is amount of nuclear facilities in this continents such as nuclear power plants fewer. So that the this topic research becomes unattractive in Africa, South America and Australia.
3.4. Citation analysis

The level of expertise of a researcher can be seen from various things. One of them is the number of papers produced and quoted by others researcher. The more papers cited by other people, the information from these papers is needed by others to conduct research. The web of science platform is used for citation analysis, it is used to analyze the number of citations in this review. Table 2 shows the top 5 cited papers for this topic research. The paper written by Pil Soo Lee with the title Development of FPGA-based digital signal processing system for radiation spectroscopy was quoted by most other researchers with a total of 33 cititations. Whereas from all papers in this study the average cititation is 7.37 per paper.

| Title papers                                                                 | Year | Citations |
|------------------------------------------------------------------------------|------|-----------|
| Development of FPGA-based digital signal processing system for radiation     | 2013 | 33        |
| spectroscopy [3]                                                              |      |           |
| Performance of a digital CdTe X-ray spectrometer in low and high counting     | 2010 | 29        |
| rate environment [6]                                                          |      |           |
| Real time digital pulse processing for X-ray and gamma ray semiconductor      | 2013 | 23        |
| detectors [7]                                                                 |      |           |
| Development of the gamma-ray analysis digital filter multi-channel analyzer   | 2011 | 21        |
| (GMCA) [2]                                                                    |      |           |
| Gamma–gamma coincidence spectrometer setup for neutron activation analysis     | 2011 | 21        |
| and nuclear structure studies [8]                                             |      |           |

3.5. Main component of spectroscopy device among papers publication

The basic instrumentation of gamma ray spectrometry system consists of a detector, pre amplifier, amplifier, high voltage power supply, low voltage power supply, analog to digital converter (ADC), MCA and a computer. In the past, most spectroscopy device used analog system, but their performance and flexibility limitations. Currently, this limitations have been overcome by high performance ICs technologies related to FPGA and ADC. This technologies have intereseted the attention among researchers to development spectroscopy device for radiation detection and measurement [1, 2]. While, disadvantages of FPGA is requirement of good knowledge of VHDL for developement of MCA [9]. The main reasons for using FPGA as MCA are parallel processing capabilities and ability to be programmed for pulse signal processing to produce spectra which resolution adjustable to ADC. ADC is a main component of digital MCA, which can directly determine performance of digital MCA [1]. High speed ADC is compatible for fast data acquisition, environmental radiation monitoring and image processing and others. ADC sampling rate is one of consideration of choose a FPGA. Generally, most this research using ADC with sampling rate 100 Msps (Mega sampling per second ) or more (19 papers). FPGA for develop MCA, mostly using FPGA from Xilinx and Altera vendors.

Based on Table 3, the three most detector which used on this research topic that NaI(Tl) (13 papers), HPGe (11 papers) and CsI(Tl) (8 papers). NaI(Tl) and CsI(Tl) are scintillation detectors, which have high detection efficiency, wide applicable temperature range of detector, low power consumption and low cost [10]. Generally semiconductor detectors such as HPGe better resolution than scintillation detectors. But the price is relatively expensive, easily damaged and must be cooled at liquid nitrogen temperatures. So many researchers are interested in using this type of scintillation detector, especially NaI(Tl) detector. For enviromental radiation monitoring such as radionuclide monitoring in seawater [10] and airborne radiation monitoring [11] using NaI(Tl) detector.
Table 3. Main components of spectroscopy device among papers publication

| Reference | FPGA type | Detector types | ADC specification |
|-----------|-----------|----------------|-------------------|
| [6]       | FPGA (not specific*) | CdTe | 14 bit, 100 Msps** |
| [2]       | Xilinx Spartan-3E | Coplanar Grid (Cd,Zn)Te, HPGe, LaBr3, NaI(Tl) and CsI(Tl) | 12 bit, 40 Msps |
| [12]      | Xilinx Spartan-3 | NaI(Tl) | 14 bit, 65 Msps |
| [13]      | Xilinx Spartan-3E | Coplanar Grid (CdZn)Te | 12 bit, 40 Msps |
| [14]      | Altera Cyclone | PIN photodiode-CsI(Tl) crystal | 12 bit, 25 Msps |
| [8]       | PCI7811R (NI) | HPGe | not specific* |
| [15]      | Altera Cyclone II | Single-photon detectors | 8 bit, 100 Msps |
| [16]      | Altera Stratix III | HPGe, NaI(Tl) | 14 bit, 150 Msps |
| [17]      | FPGA (not specific) | Au-Si surface barrier | 12 bit, 100 Msps |
| [18]      | Xilinx Virtex-4 (2 pcs) | CsI(Tl) | 14 bit, 250 Msps |
| [19]      | FPGA (not specific) | not specific | 12-bit, 40 Msps |
| [20]      | FPGA (not specific) | Coplanar Grid (CdZn)Te | not specific |
| [3]       | Xilinx Virtex-5 | CsI(Tl) | 14 bit, 150 Msps |
| [7]       | Altera Cyclone | CdTe, HPGe | 14 bit, 100 Msps |
| [21]      | Xilinx Spartan-3 | (BC-400),CsI(Tl) crystal and BGO crystal | 12 bit, 200 or 150 Msps |
| [1]       | Altera Cyclone III | NaI(Tl) | 14 bit, 65 Msps |
| [22]      | Xilinx Virtex-4 | Gas detector | 14 bit, 40 Msps |
| [23]      | Xilinx Spartan-6 | CsI(Tl) crystal | 12 bit, 40 Msps |
| [24]      | Xilinx Virtex-4 | Gas detector | 14 bit, 40 Msps |
| [11]      | FPGA (not specific) | NaI(Tl) | not specific |
| [25]      | Xilinx Virtex-4 | HPGe | 14 bit, 100 Msps |
| [26]      | FPGA (not specific) | NaI(Tl) and NIM Pulser | 40 - 100 Msps |
| [27]      | Xilinx Spartan-3 | HPGe, NaI(Tl), and CsI | up 16 bit, 65 Msps |
| [9]       | Altera MAX 7000 | HPGe | 14 bit, 100 Msps |
| [28]      | FPGA (not specific) | NaI (Tl) | not specific |
| [29]      | Xilinx Spartan-6 | HPGe | 14 bit, 150 Msps |
| [10]      | FPGA (not specific) | NaI (Tl) | 12 bit,20 Msps |
| [30]      | FPGA (not specific) | HPGe | 14 bit, 250 Msps |
| [31]      | high-speed FPGA | Sintilator detector | 12 bit, 500 Msps |
| [32]      | Altera Cyclone IV | Si(Li) | not specific* |
| [33]      | Xilinx Spartan-6 | LaBr3 | 14 bit, 100 Msps |
| [34]      | Altera Cyclone IV | HPXe | 12 bit, 65 Msps |
| [35]      | Altera Cyclone III | NaI(Tl) | 14 bit, 125 Msps |
| [36]      | Xilinx Spartan-6 | NaI (Tl), LaBr3, HPGe | 16-bit, 125 Msps |
| [4]       | Xilinx Zynq-7000 | NaI(Tl) and HPGe | 12 bit, 1 Msps |
| [37]      | Altera Cyclone III | CsI (Tl) | 14 bit, 100 Msps |
| [38]      | Altera Cyclone III | NaI (Tl) | 16 bit, 100 Msps |
| [39]      | Xilinx Zynq-7000 | not specific/ pulse generator | 12 bit, 2 Msps |

* not specific : Hardware specifications not mention in papers.

3.6. Various themes research publication

In this section, We divide 38 selected papers based on emerging research themes that is design and construction MCA, digital pulse processing, experiment using various detector, comparison with comercial MCA and overview of MCA for spesific application. Sum of all the research themes more
than the total number of papers selected because in one papers there is which more than one research theme. Table 4 is research themes among papers publications.

| Themes research                        | Study references                           |
|----------------------------------------|--------------------------------------------|
| Design and construction of MCA         | 21 papers [1-4, 9, 10, 13-15, 19-21, 23, 28, 29, 32, 33, 36-39] |
| Digital signal processing algorithms   | 28 papers [2, 3, 6-8, 11-13, 15-19, 21-28, 30, 31, 34-38] |
| Experiment using detector              | NaI(Tl) [1, 2, 4, 10-12, 16, 26-28, 35, 36, 38]; CdTe [6, 7] |
|                                        | HPGe [2, 4, 7-9, 16, 25, 27, 29, 30, 36]; Au-Si surface barrier [17] |
|                                        | CsI(Tl) [2, 3, 14, 18, 21, 23, 27, 37]; Coplanar Grid (Cd,Zn)Te [2, 13, 20]; SiLi [32]; LaBr3 [2, 33, 36]; gas detector [22, 24]; HPXe [34] |
| Comparison with comercial MCA          | 7 papers [2, 4, 7, 17, 34, 36, 38] |

3.6.1. **Design and construction of MCA.** Spectroscopy device using digital MCA produce better energy resolution and stability than analog MCA [2]. Many researchers create design MCA based FPGA. The main reasons for using FPGA as MCA are parallel processing capabilities and ability to be programmed for pulse signal processing corresponding of application [1, 2]. Most of the studies in this theme that is 21 papers from 38 of total paper. Various types of FPGA are used in this research such as Xilinx Spartan-3, Xilinx Spartan-6, Xilinx Virtex-4, Xilinx Zynq, Altera Cyclone and others.

3.6.2. **Digital signal processing (DSP) algorithms.** For measure pulse height (peak detection) and pulse shape, then signal output from ADC should be done digital signal processing. Determination of maximum pulse height aim to determine of the radiation energy from radioisotop source. Meanwhile determination of the pulse shape which can be used for various purposes such as detection of gamma-ray interaction depth and identification of radioisotop [3]. As much of 28 papers have been published review related digital signal processing algorithms. The FPGA is is programmed for digital pulse shaping using DSP algorithms such as moving window deconvolution (MWD) [2, 13], convolution [12], least-mean-square (LMS) [22], discrete fourier transform (DFT) [22], fast fourier transform (FFT) [11, 17], trapezoidal, gaussian and cusp [25], digital CR-RC\(^m\) shaping filter [36], high-speed waveform sampling [38], mexican hat wavelet pulse (MHWP) shaping filter [35], baseline restoration [34], real time algorithms [7, 15, 18, 21, 30, 31], lagrange interpolation [19] and others.

3.6.3. **Experiment using detector.** To evaluated this MCA performance several experiment using detectors, function generator and sources. Result MCA linearity using function generator pulses show that good correlation between the input pulses voltage and the channel is shown [2, 4, 9, 14, 17, 39]. Researchers using detector type according to requirement and spectroscopy applications. Detector which used to experiment is NaI(Tl), HPGe, CsI(Tl), Coplanar Grid (Cd,Zn)Te, LaBr3, CdTe, gas detector, HPXe, SiLi and Au-Si. This shows that MCA based FPGA are suitable for various types of detectors. Main requirements of an multichannel analyzer is the energy resolution. The experiment using various detector and standar sources such as Cs-137, Co-60 and others shown that MCA based on FPGA produce good energy resolution [1, 2, 4, 9, 17, 36].

3.6.4. **Comparison with comercial MCA.** Performance MCA based FPGA compare with comercial MCAs such as from ortec[2, 4] and canberra [4, 36]. The results energy resolution measurements and spectra measured with various detector show that performances MCA based on FPGA can compete with the comercial MCA [2]. However design of MCA based on FPGA is smaller and low cost [4, 17].
3.6.5. **Overview of MCA for specific application.** The MCA based on FPGA for spectroscopy device has several benefits compared to commercial spectroscopy devices. The most important one is the flexibility of the system, which does not limit it to spectroscopic application. The main components FPGA and ADC allow various of spectroscopy application just by changing the programming in FPGA. The Commercial spectroscopy systems don't usually allow such changes in digital signal processing code or functions [2, 4]. This spectrometer used for various of specific application such as enviromental radiation monitoring, security inspection, diagnostic medicine, industrial imaging, neutron monitor and synchrotron radiation facilities. Table 5 show specific application among papers publications.

| Specific application                                      | Study References              |
|----------------------------------------------------------|-------------------------------|
| Enviromental radiation monitoring                       | [2, 8, 10, 11, 13, 15, 21, 34, 37] |
| Surveying (portable application)                        | [14, 23, 29]                 |
| Diagnostic medicine(computed tomography and mammography)| [1, 6, 7, 18]                |
| Neutron monitoring                                      | [22, 24]                     |
| Industrial imaging                                      | [1, 3, 7, 19]                |
| Security screening                                      | [7, 14, 23]                  |
| Ion beam induced luminescence (IBIL)                     | [32]                         |
| Synchrotron radiation facilities                        | [33]                         |
| Primary activity measurements                            | [16]                         |
| Neutron imaging                                         | [31]                         |
| Gamma spectroscopy (general)                            | [4, 9, 12, 17, 20, 21, 26-28, 30, 35, 36, 38, 39] |

*general: specific application not mention in papers.

3.7. **Future research of development MCA based FPGA for enviromental radiation monitoring based gamma spectroscopy**

Many scientific findings show that radiation is around us even in our bodies. However, because radiation cannot be detected by the five human senses, so its existence is not realized [40]. In many countries around the world, in order to protect the public from radiation exposure, usually the government or relevant authorities build a system of environmental radiation monitoring around the nuclear area [41-44]. So necessary development of environmental radiation monitoring systems.

Research related to the development of MCA based FPGA for gamma spectroscopy during last 10 years has become a hot research topic, especially in Asia who are interested in the use of nuclear technology. The resulting performance and spectrum are very satisfying. The utilization of FPGA as an MCA allows it to be programmed for realtime pulse signal processing and data acquisition. Based on this advantages, the MCA based on FPGA can supports future research in the development of low-cost environmental monitoring radiation devices based gamma spectroscopy.

In the environmental radiation monitoring system there is a gamma spectroscopy system and a weather monitoring system. Weather factors are crucial in the measurement of radioactive sources [43]. None of the 38 selected papers have conducted research to connect and process data from weather sensors using FPGA (also used as MCA). So this research needs to be done.

From this SLR, for environmental radiation monitoring applications used NaI(Tl) detector because of the advantages of the high detection efficiency, wide applicable temperature range, stable performance, low cost and low power consumption. This system requires fast data acquisition, so it requires high speed ADC. This has become one of the considerations in the selection of FPGA specifications.
4. Conclusions
This study explored a systematic literature review of MCA based FPGA for gamma spectroscopy and answering the research questions. Based on papers publication trends during last 10 year show that research of MCA based on FPGA become hot topic mainly in Asia continent (53%). This research topic is mostly published in journals and conferences related to nuclear instrumentation and applications of radiation and radioisotopes. The average citation from 38 papers is 7.37 per paper.

Among the emerging research themes, design and construction of MCA and a digital signal processing algorithms have interested the attention among researchers. MCA based on FPGA compatible to various detectors like NaI(Tl), HPGe, CsI(Tl) and others. Based on reviews of experiment results show performances of MCA based on FPGA can compete with commercial MCA. But, MCA based on FPGA has several benefits which allow various of spectroscopy application just by changing the programming in FPGA. During this review, it was noted that MCA based FPGA applied for various gamma spectroscopy applications such as enviromental radiation monitoring, diagnostic medicine, industrial imaging and others. In some gamma spectroscopy applications, this MCA leads to positive results with cost reduction. Based on this study, then MCA based FPGA can used for supports future research in the development of environmental radiation monitoring devices based gamma spectroscopy with low cost.

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