ISSN: 2633-4828 Vol. 5 No.4, December, 2023

International Journal of Applied Engineering & Technology

OPTIMIZING DESIGN FLEXIBILITY IN CONTEXT-AWARE IOT EDGE DEVICES: A FRAMEWORK FOR DESIGN SPACE EXPLORATION

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ABSTRACT

This paper introduces a framework aimed at optimizing the design flexibility of context-aware IoT edge devices through systematic design space exploration (DSE). Context-adaptive capabilities are crucial for IoT devices operating at the edge, where varying environmental conditions and user contexts demand efficient and adaptable solutions. The proposed framework integrates scenario-based analysis and fitness prediction techniques to explore and evaluate diverse design options, ensuring robust performance across dynamic contexts. Experimental results demonstrate the framework's effectiveness in enhancing design adaptability and efficiency in IoT edge environments.

Keywords: Design Space Exploration, IoT Edge Devices, Context-Awareness, Design Flexibility, Scenario-Based Analysis, Fitness Prediction

I. INTRODUCTION

The Internet of Things (IoT) represents a transformative network where physical objects are embedded with electronic technology to collect, process, and share data [1]. This paradigm distributes computing tasks across networked devices, crucially enhancing operational efficiency and responsiveness. However, IoT edge devices, tasked with significant computing responsibilities, operate under stringent power constraints that limit data transmission to higher cloud layers [2]. This constraint not only challenges scalability but also raises security concerns, particularly in applications like medical wearables and surveillance systems [3].

Traditionally, IoT sensor nodes are viewed as devices that capture and transmit scalar data such as temperature and humidity [4]. This narrow perspective overlooks sensors capable of processing complex data vectors, such as image or audio sensors, which are increasingly relevant for IoT applications. Addressing the intersection of data complexity and processing demands necessitates reevaluating design constraints to optimize latency and energy efficiency for these advanced sensors.

Design Space Exploration (DSE) methodologies, originally developed for multiprocessor systems and Field Programmable Gate Arrays (FPGAs), offer a structured approach to co-design hardware and software in embedded systems [6]. These frameworks balance conflicting objectives like energy consumption, cost, and memory usage, crucial for optimizing system performance across diverse application requirements. Different DSE techniques—prototype-based, simulation-based, and analysis-based—vary in their trade-offs between modeling accuracy and design efficiency.

Edge computing, facilitated by IoT edge devices embedded in wearable accessories, exemplifies near-sensor processing, where data is processed locally to minimize latency and security risks associated with data transmission [7]. This approach enhances user interaction by facilitating real-time data analytics and reducing dependency on centralized cloud services. Moreover, advancements in wearable IoT systems have introduced opportunistic sensing strategies to balance energy consumption with data acquisition, especially under dynamic operational conditions [8].

While existing research has focused on optimizing specific IoT scenarios, a comprehensive DSE methodology capable of integrating multi-objective optimization—balancing performance, energy efficiency, and cost—remains a critical gap. This paper proposes a framework for Design Space Exploration tailored for context-aware IoT edge devices. Section II reviews current IoT application trends, highlighting the need for adaptive and efficient edge computing solutions. Section III details the proposed DSE framework, emphasizing its utility in optimizing IoT device architectures under varying operational conditions. Section IV presents experimental results and observations, underscoring the framework's effectiveness in enhancing design flexibility and performance. Finally, Section V concludes with a summary and outlines future research directions in advancing IoT edge device design methodologies.

II. LITERATURE SURVEY

Lomotey R.K, Pry J, and Sriramoju S, et. al. [9] have proposed a wearable IoT information gushing design, which has offered the recognizability of information courses from the starting premise to the wellbeing data conspire. So as to overpower the mapping troubles and indistinguishable device information to clients, they have advanced an improved Petri Nets administration exemplary. The result from different experiential evaluations has led in a constant wearable IoT ecosystem, which has demonstrated a few methodologies: the created system has appropriate for straightforwardness of wellbeing data and some different procedure like linkability and unlinkability.

Rault. T, Challal.Y, Bouabdallah. A, Marin. F, et al. [10] evaluated methods for reducing energy usage in wearable sensors for medical applications. In contrast to a static DSE, opportunistic sensing solutions take dynamic effects on the resource consumption trade-off into consideration. For examples, if a reduced signal entropy is observed, an adaptive sampling technique may reduce sampling rates.

Sharma V, Song F, and Atiquzzaman, M, et al. [11] have introduced a novel methodology for vitality effectiveness of device disclosure in 5G-situated IoT just as Body Sensor Networks (*BSNs*) with the utilization of complex Unmanned Aerial Vehicles (UAVs). They have likewise proposed a down to earth engineering, which has used a XML (Extensible Markup Language) outlines for the exhibition of device disclosure dependent on the expense of systems state and available vitality. The achieved arrangement has the capacity of allowing devices that were vitality productive with 78.4% reduction in the total utilization of vitality when contrasted with traditional arrangements. The advantage of UAVs in vitality proficient systems administration was additionally shown with the guide of arithmetical investigation that has proposed 75 % improvement in the utilization of vitality in the current systems.

Pimentel, Andy et. al. [12] The Embedded Systems Design Space Exploration Tutorial. For determining the best tradeoff between various design objectives and their tradeoffs, modern design space exploration techniques are essential, since inserted systems become increasingly complex and new applications like the Internet of Things (IoT) require numerous design limitations. An organized understanding of the field of design space exploration for inserted systems is provided by this instructional activity.

Shaikha & Zeadally et. al. [13] focused chiefly on Wireless Sensor Networks (WSNs) which have certain qualities like unavoidable nature and wide sending in IoT, digital physical systems and so forth. So as to defeat the hindrance of WSN innovation for example restricted utilization of vitality, effective and superior vitality gathering systems have been investigated by these creators. However, they have proposed vitality expectation models the creators examined about certain difficulties that are as yet should have been tended to in Wireless Sensor Networks.

Ingo Stierand, Sibylle Fröschle, Sunil Malipatlolla, Alexander Stühring, Stefan Henkler, et. al. [14] Embedded system design space exploration that integrates the security aspect. In order to create an architecture that is both cost-effective and secure, this analysis aims to integrate the security constraints into an automatic DSE procedure. In particular, described approach creates a formal security concept for a given system and fed into the DSE process along with other parameters to create an architecture that satisfying the security and real-time requirements. Using an analysis of an embedded automotive system, the proposed method is also evaluated.

Beretta. I, Khaled. N, Rincon. F, Rana V, Atienza D, Grassi P.R, Sciuto D, et al. [15] provided a model-based design optimization to accurately estimate the power requirements of a wearable sensor node. To analyze system configurations and relative trade-offs, the author identifies a multi-objective search algorithms. With a fixed system architecture, the process remains application-driven.

Table-1 Table summarizing the literature

Authors and Reference	Focus of Study and Contribution
Lomotey R.K, Pry J, Sriramoju S, et al. [9]	Proposed a wearable IoT data streaming design using enhanced Petri Nets. Evaluated for health data transparency and linkage management.
Rault. T, Challal.Y, Bouabdallah. A, Marin. F, et al. [10]	Evaluated methods to reduce energy consumption in medical wearable sensors, emphasizing opportunistic sensing for dynamic resource management.
Sharma V, Song F, Atiquzzaman, M, et al. [11]	Introduced a methodology for energy-efficient device discovery in 5G-oriented IoT and Body Sensor Networks using UAVs and XML schemas. Achieved significant energy savings.
Pimentel, Andy et al. [12]	Tutorial on Design Space Exploration (DSE) techniques for embedded systems, essential for optimizing IoT applications and managing design constraints.
Shaikha & Zeadally et al. [13]	Explored efficient energy harvesting systems for Wireless Sensor Networks (WSNs) to overcome energy limitations and deployment challenges.
Ingo Stierand, Sibylle Fröschle, et al. [14]	Integrated security constraints into DSE for embedded systems, proposing a formal security concept to meet real-time requirements effectively.
Beretta. I, Khaled. N, Rincon. F, et al. [15]	Developed a model-based optimization for power estimation in wearable sensor nodes, utilizing multi-objective search algorithms to analyze system configurations.

This table provides a concise overview of each study's focus, contributions, and key findings in the domain of IoT, wearable sensors, and embedded systems design space exploration.

III. DESIGN SPACE EXPLORATION FRAMEWORK

Figure 1 demonstrates the process of the Design Space Exploration Framework for Context-Adaptive Wearable IoT Edge Devices.

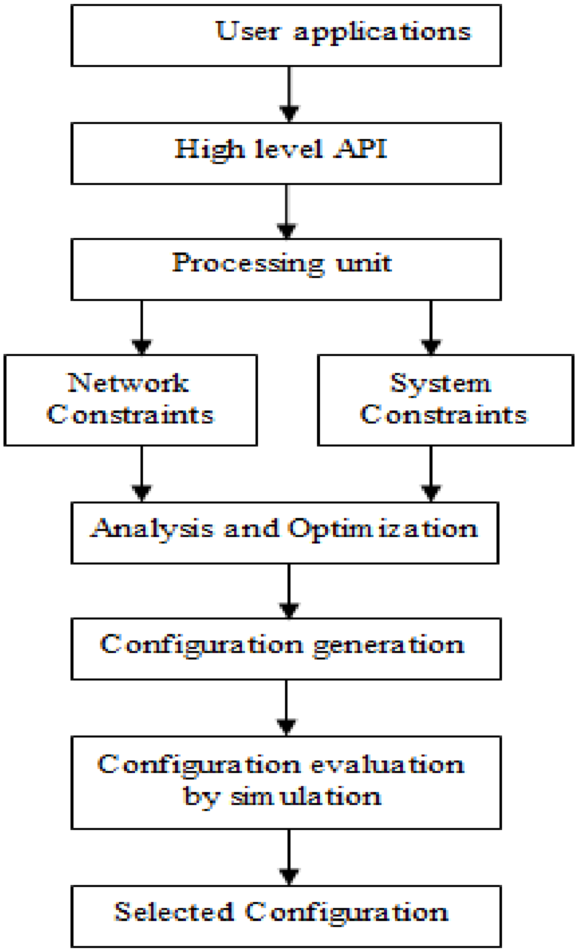

Fig. 1: Design Space Exploration Framework for Wearable IOT Edge Devices

The components of a microcontroller (μC) wearable IoT devices include data processing algorithms, multiple sensors, memory, and a radio modules for data transmission. As a result, optimizing resource-constrained IoT edge devices should be given a high priority during the design phase. A wide range of possible options are considered during the design of an IoT device, and the best combination of software and hardware is chosen. There is a possibility that particular system requirements, such as energy efficiency and retrieval speed, will not be met by certain system configurations. Manual exploration of embedded systems is frequently difficult due to the size of the architectural design space. A computational framework for finding the best configurations is provided by automated Design Space Exploration (DSE).

A dynamic sampling approach used by wearable Internet of Things devices called context-adaptive sampling modifies the sampling rate of the sensor based on a context measure, attempting to reduce energy consumption It modifies the sampling rate of the sensor based on a context measure. The stochastic and variable type of human behavioral patterns, which have a substantial impact on the resource-performance trade-off are important for variability through context-adaptive sampling patterns. Therefore, integrating viable configurations that can satisfy system requirements under dynamically changing conditions and clearly demonstrate the context-adaptive system behavior in design exploration and simulating the systems with real sensor data is the main challenge for designing a context-adaptive wearable IoT device with the framework described.

The Python-based high-level API (Application Program Interface) that developers can use to customize the framework's operation. It does three things: i) to let users choose between different operation modes for the framework ii) to give the framework deployments on edge devices configuration parameters and iii) to produce a collection of source files that offer a description of the framework that is particular to the platform.

Accessing information stored in the global memory can be made more costly by using a cache memory. DMA transactions are used to transfer information from the global memory to the local memory in a typical data management pattern, and Direct Memory Access (DMA) is used to return the processed data to the global memory. Very Long Instruction Word (VLIW), Single Instruction, Multiple Data (SIMD), and Multiply-Accumulate Operations (MACs) are typically supported by multiple vector processing units (VPUs) with excellent efficiency. An operating system is frequently run by RISC (Reduced Instruction Set Computer) processors. They also handle things like interrupting.

The interactions between various factors, including system resource constraints, and network communication capabilities, application parallelism, all have an effect on performance as a overall. Computation and communication can be dynamically serialised or parallelized at the intra- or inter-device level during execution. It is necessary to carefully consider the possibility of overlap between data processing and communication tasks in order to accurately estimated application performances. To quickly discover near-optimal solutions and satisfy multiple system objectives, the design of these systems requires effective modeling and optimization methods. Designers can use the Design Space Exploration (DSE) tools to find the best system.

A design candidate for the simulation is chosen during configuration generation. A component set is chosen in the first stage for each functionality, and it is indexed by the index set q_{ξ}^{c} as follows:

$$q_{\xi}^{c} \subseteq q_{\xi} \ldots . (1)$$

Where the index set q_{ξ}^{c} is a subset of that set. Overall, configuration is made up of a collecting E of system components sets that are indexed by a collecting Q^{c} of indexing settings are shown in the following expression:

$$E = \left\{ e_{\xi}^{c} \right\} \xi \epsilon \xi \ldots . (2)$$

$$Q^{c} = \left\{ q_{\xi}^{c} \middle| \xi \epsilon\, \xi \right\} \ldots . (3)$$

In the second stage, For each element, $e_{\xi,q} \ \epsilon \ e_{\xi}^{c}$ The following are the component parameters established $w_{\xi,q}^{c}$ selection process:

$$w_{\xi,q}^{c} = \left\{ w_{\xi,q,w} \right\} w \epsilon\, w_{\xi,q}^{c} \ \ldots . (4)$$

$$w_{\xi,q}^{c} \subseteq w_{\xi,q,w} \ldots . (5)$$

where the index set $w_{\xi,q}^{c}$ is represented by a subset by $w_{\xi,q,w}$. A system configuration is made up of a collection Wc of index sets and a collections Ω of system component parameters, which are expressed as follows:

$$\square | E, \Omega \subseteq \ \square | \varepsilon, \Omega \ldots . (6)$$

There are two sets of metrics used in the configuration evaluation. The following defines the benefit metric set:

$$\pi = \{ \pi^{P} (\square | E, \Omega) \} \, p\epsilon p \ldots \ldots (7)$$

$$p = \left\{ p \middle| p \epsilon\, N_{1}, p \leq N_{p} \right\}, \ldots \ldots (8)$$

A benefit metric is represented by element $\pi^{P}(\aleph | E, \Omega)$, and the amount of benefit metrics is Np. The benefits requirements set is applied to the benefits metric set in the following order:

$$Z_\pi = \{Z_\pi^p\}\ p\epsilon p \ldots\ldots (9)$$

The cost requirement set is subject to the cost objective set ρ in the following ways:

$$Z_p = \{Z_p^r\}\ r\epsilon r \ldots (10)$$

The design's trade-offs are reflected in the optimization's set of mutually conflicting solutions. To determine optimality, one can commonly use the Pareto-dominance concept, which states that a decision maker preferred one configurations over another if it is equal or greater in all objectives and definitely greater in at least ones. To balance event retrieval performance and resource usage, the simulation based approach's DSE structure considers a wide range of configuration spaces.

IV. RESULT ANALYSIS

This section analyses the performance of the Design Space Exploration Framework for Context-Adaptive Wearable IoT Edge Devices. Ten healthy volunteers between the ages of 20 and 30 who were divided into four females and six males maintained the *electromyography* (*EMG*) monitors for the entire day. The simulation's application details were sensor readings taken at a continuous sampling rate of 256 Hz. The glasses were worn until bedtime after being fastened to the head. Participants were permitted to remove their eyeglasses when there was a possibility of water contamination. Participants manually recorded eating events with a one-minute resolution in a diet journal.

Our measurements and system requirements are execution time, energy consumption, precision, and recall. Additionally, these indicate the elements that have an impact on the system requirements. The execution time provides as a measure for computational complexity. The Myriad development kit's recommended functions were used to measure execution time. On-chip sensors offered by the Myriad 2 evaluation board, which detect the flow of current multiple power rails, have been used to compute energy consumption with high accuracy.

Fig. 2, and Figure 3 display the energy consumption and execution time of the described framework for wearable edge devices. Execution time and energy consumption both continue to reduce gradually as the number of processing units increases.

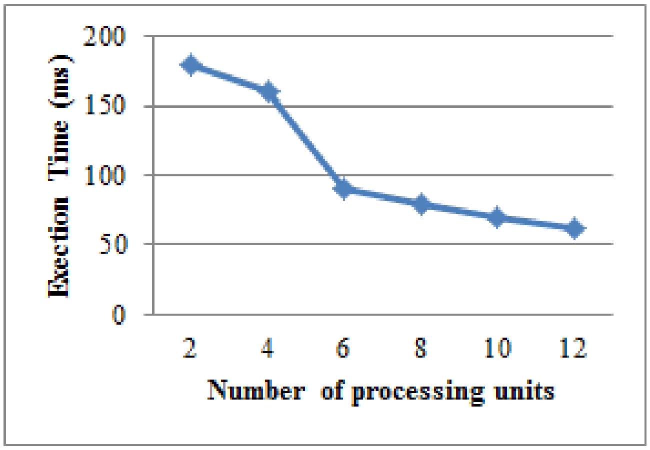

Fig.2: Evaluation of Execution Time

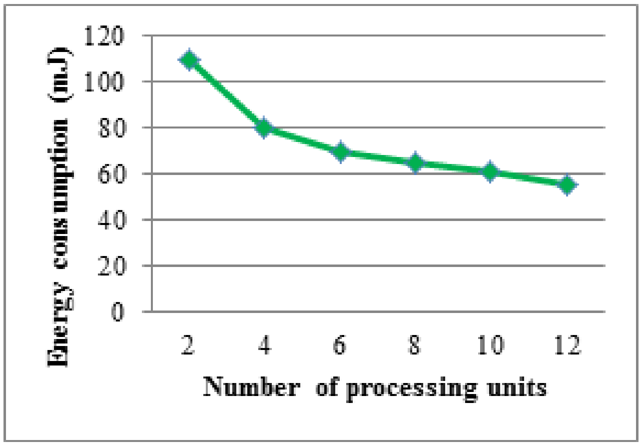

Fig.3: Evaluation of Energy Consumption

During the course of each layer's execution, there are two tasks that are carried out: i) It manages global and local memory DMA transaction communications and ii) it uses computation to actually process data. It is essential to keep in mind that the DMA engine becomes congested and the communication overhead increases when multiple VPUs request DMA transactions concurrently. As a result, while the communication overhead goes up when parallelism is used, the computational overhead goes down when more processing units are used.

The comparative performance of the described framework is analyzed by using two performance parameters as Precision and Recall. The Design Space Exploration framework for Context-Adaptive Wearable (DSE-CAW) IoT Edge Devices was compared to conventional IoT device design space exploration.

$$Precision\ P = \pi^{1}(\square|E,\Omega) \ldots..(11)$$

$$Recall\ R = \pi^{2}(\square|E,\Omega) \ldots\ldots(12)$$

This algorithm's recovery performance must be adequate from an applications view. The Z_{π}^{1} and Z_{π}^{2} retrieval performance requirements are often determined by expert knowledge.

Table 1: Comparative Performance Analysis

Model	Precision (%)	Recall (%)
DSE-CAW IoT Edge Devices	97	96
DSE of IoT devices	65	64

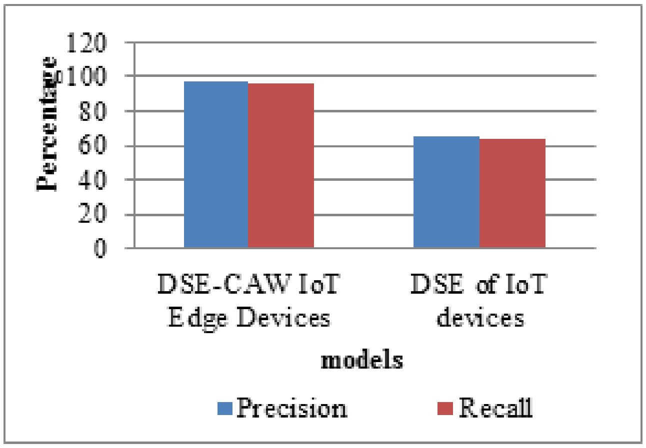

Fig.4: Comparative Performance Analysis

The results show that the suggested design space exploration framework outperforms the other models in terms of execution time, energy usage, precision, and recall. Applications that are not specifically being considered do not require any modifications to the design space exploration framework that has been described. To drive the simulation, they believe it is necessary to match the DSE method with appropriate sensor data. DSE may required approximate rules for more extensive design spaces. However, the extensive search that was used in this case is still an option that can be used to make coarse design choices before going into more design elements in local explorations.

V. CONCLUSION

The analysis introduces a Design Space Exploration Framework tailored for Context-Adaptive Wearable IoT Edge Devices. A constrained optimization problem was formulated to determine the optimal system configuration aligned with application-specific requirements. Simulation plays a crucial role in revealing the compatibility of system components. Results demonstrate that the proposed framework surpasses alternative models in key metrics such as execution time, energy consumption, precision, and recall. Dynamic resource management enables wearable IoT devices to adapt their configurations in real-time, responding to evolving circumstances. Further research is needed to effectively quantify privacy and security risks using standardized metrics.

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