Feasibility Study of a Logic Gate for the Ternary Operation of a Process Unit

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***Abstract*—Towards the end of the previous century, the former Soviet Union attempted to develop a computer based on the ternary operation system. However, this project ultimately failed to succeed for various reasons. The most commonly used computer system in the world today is founded on the binary computing format. Both ternary and traditional computers rely on the foundational structure of the binary system, which originated from gate switching in logic circuits and voltage differences in signal transmission. However, is the number two always the optimal choice for computation? Extensive research in this area was conducted in the former Soviet Union. However, there has been limited research and development in this direction. This phenomenon piqued our interest, and thus this study conducted a comprehensive literature review on ternary computers to provide an all-inclusive overview of the field. This study gathered a significant amount of literature on ternary arithmetic units, covering topics such as the ternary concept, ternary architecture, ternary energy efficiency, etc. In summary, this body of literature delves into the potential for developing computers that employ ternary arithmetic units and discusses the prospect of such machines. In a relatively less-explored field, this study conducted a literature review on ternary computers. It contributed new insights that could be valuable for the future development of ternary arithmetic units.**

***Keywords*—ternary computer, ternary arithmetic units, energy efficiency, computer development**

I. Introduction

The former Soviet Union played an important role in the development of ternary computing, particularly with the introduction of the balanced ternary system. This unique variant of ternary computing employed the use of −1, 0, and 1, supplemented by a carry, to perform information processing more efficiently than the traditional binary system.

Early computer design efforts predominantly relied on binary representation due to the simplicity of implementing decimal numbers through binary switches. However, it became apparent that binary might not be the most efficient base system. This realization led the former Soviet Union to explore the possibilities of ternary computing. The Soviet Academy of Sciences proposed the concept of a ‘ternary computer’ to cater to the specific requirements of tasks like weapons design, where the ability to transmit information rapidly and stable is of paramount importance, making the ternary system an attractive choice [1].

This study explores the possibility of designing a more efficient computing system. Modern computer design studies predominantly emphasize binary computer design concepts and content. Consequently, this study lacks substantial experience and specific experimental research regarding the mathematical design concepts and practical application impact of ternary computers. Hence, this study conducted a literature review to gather and summarize data on ternary computers, aiming to demonstrate their feasibility. Additionally, this study aimed to conduct a more comprehensive literature review to address the scarcity of content in this field. Furthermore, this study aimed to offer a more in-depth introduction to future ternary research and its associated circuit design experiments.

II. Foundational Study

A. Efficiency

Ternary demonstrates significant efficiency advantages over binary in various aspects, a superiority that finds application across numerous domains. Take information storage, for instance. Ternary possesses the ability to store more data while maintaining the same resource consumption level.

For example, for the representation of the number 6: in binary, it’s ‘110’, while in ternary, it’s simply ‘20’. This simple comparison highlights the ternary’s advantage – It can represent equivalent numerical values in a more concise manner, which is crucial for both data transmission and storage.

Another advantage of ternary is its application in computer hardware. Compared to binary, ternary can make more efficient use of computational resources, thereby enhancing computing speed and efficiency. This is particularly important in applications requiring rapid processing of large datasets, such as artificial intelligence and scientific computing.

In summary, ternary not only excels in information storage but also demonstrates outstanding performance in computer hardware and various other fields. Consequently, it may become increasingly significant in future technological developments [2].

In computer system operations, the absence of intermediate logic between “true” and “false” is rather inconvenient, yet these intermediate logics play a crucial role. They enable us to handle information more flexibly, not limited to binary true-false judgments alone. With intermediate logic, we can deal with fuzzy or uncertain situations, making computer systems more intelligent and adaptable. These intermediate logics also play a critical role in various applications, including artificial intelligence, natural language processing, machine learning, and more. Therefore, their existence is paramount for the development of modern computing systems and technologies [3].

Multivalued logic is a promising choice for future computer technology, offering a range of advantages compared to binary circuits. In multivalued logic, information is not limited to just two states, true and false; it can represent a broader spectrum of states, providing computers with greater flexibility when dealing with complex data and problems. Multivalued logic also helps reduce circuit complexity, lower power consumption, and improve computational efficiency. These attributes are crucial for the development and enhancement of future computing devices, especially in fields like artificial intelligence, big data processing, and quantum computing. Therefore, multivalued logic is poised to play a pivotal role in the future of computing technology [4].

According to the article that is found on Google Scholar, it became evident that ternary logic harbors immense potential. This research has introduced an innovative, low-power ternary logic circuit structure aimed at enhancing the efficiency and performance of logic circuits. Traditional logic circuits predominantly rely on binary logic gates to execute various computational tasks. However, as computer technology advances, conventional binary logic circuits have started revealing certain limitations.

Our newly proposed ternary logic circuit structure effectively overcomes these limitations by amalgamating ternary functions into a single, integrated ternary logic gate. The core concept underlying this approach is the fusion of multiple ternary logic gates to create more intricate logic circuits. This concept is not limited to balanced and unbalanced ternary logic but can be adapted to various ternary arithmetic logic circuits through design enhancements.

Given its ability to offer enhanced performance while simultaneously reducing energy consumption, this innovation holds great promise for future electronic devices and computer systems. This is a positive indication that perhaps the ternary unit can be implemented, but it just needs further research [5].

B. Mathematical Foundation

This book is a good explanation of the important advantages of the ternary system over the binary system, and also a good explanation of the design of the ternary circuit and the advantages of the ternary system [6].

Mathematically, how efficient a base is depends on how much data it can represent while consuming the same amount of resources [7]. Because an N-digit base-X number can represent $M = (X)^N$ numbers, $P = NX$ states.

If we establish that for base X, the product of the number of digits required to represent M numbers (N) and its base (X) is the resource consumption (R) to represent M numbers, then its efficiency(E) is $\frac{M}{R}$, and smaller quotient indicates a higher efficiency in that base.

So, the number of digits required to represent M numbers in base X is $\log_X M$ and the resource consumption is:

$$R = X \times log_X M \tag{1}$$

Its efficiency is

$$E = \frac{M}{R} = \frac{M}{X \times log_X M} \tag{2}$$

When we take the derivative of this function, we can determine that the original function reaches its maximum value when X equals e.

$$\frac{dE}{dX}\left(\frac{M}{X \times log_X M}\right) = \frac{M \times (ln\, M - log_X M \times (ln\, X)^2)}{X^2 \times (ln\, X)^2 \times (log_X M)^2} \tag{3}$$

The function E reaches its stationary point when x = e. At this point, the efficiency (E) is maximum, which means the fewest states are required to represent the same number of values, resulting in the highest efficiency. So in theory, the efficiency is highest in the base-e system, but we cannot define the base-e system. 3 is closer to e than 2, so the ternary system (base-3) is more efficient.

Multi-valued logic, as opposed to binary logic with the same number of logic bits, can represent exponentially more data/information. In this paper, this study demonstrates the design of basic ternary logic gates (e.g., inverters, NAND, NOR) and ternary arithmetic circuits (e.g., ternary decoder, 3:1 multiplexer, ternary half-adder) using GNRFET. This study performs a comparative analysis of GNRFET-based ternary logic gates and circuits with their counterparts based on traditional CMOS and CNTFET technologies using metrics such as delay, total power, and Power-Delay-Product (PDP) [8].

C. Practical Applications

Ternary logic has extensive applications in the field of information security, and ternary password-sharing schemes can create a secret-sharing environment [9]. After that, ternary logic also has great practical value in optical fiber communication, as it can utilize horizontally polarized light, vertically polarized light, and light with no intensity to convey information [10]. Followed by another research in which ternary logic can also be applied in computer architecture, expressing information through different polarized states of light [11]. Because the ternary system is simple, stable, and efficient, it can be applied in many fields. For example, the ternary filter. The ternary filter not only has a simple structure but also has a mature theory that makes it comparable to the old algorithm. Very has the research value [12]. The ternary computing framework can reduce errors in estimating power consumption when sensing input currents, and this method can track dynamic currents with continuously variable loads [13].

Another research shows that ternary logic also has significant advantages in data processing, requiring less time for data scanning and enabling faster data stream searches [6]. Also, the secure exchange of addressable cryptographic tables between the parties involved is an integral part of the key scheme in a public key infrastructure. By using ternary logic and exchanging dynamically generated public keys, communication between the parties can occur over untrusted channels, thereby enhancing the level of network security [14]. Through model validation, the ternary adder has a smaller area, and it also reduces the circuit's static power while decreasing the number of transistors [15]. Ternary logic can also be applied in the field of copyright protection. The proposed stereo image zero-watermarking algorithm based on ternary logic exhibits strong robustness against various asymmetric and symmetric attacks, providing advantages over other zero-watermarking algorithms [16]. What's more, ternary logic can be applied in the field of human action recognition, where it serves as an image filter to enhance the distinguishability of similar actions, meeting the requirements of real-time action recognition tasks [17].

In cases where the neural network structure and ternary weight values are known in advance, customizing the hardware architecture enables efficient neural network inference. Through such specialization and optimization, the hardware implementation achieves remarkable performance [18]. Ternary resistors, optimized with fast switching, high transconductance, and low current leakage characteristics, have increased their data density and achieved improvements in switching speed [19]. A new texture descriptor named Otsu Enhanced Local Ternary Pattern (OELTP) is introduced for feature extraction from these blocks. In contrast to previous techniques, this method employs energy to reduce feature dimensionality, thereby improving efficiency. The approach begins by converting the image to the YCbCr format, extracting chrominance components, and segmenting them into overlapping blocks for local feature extraction. Experimental results demonstrate that this method achieves remarkably high accuracy on various datasets, showcasing its superiority in image forgery detection [20]. Ternary weight filters are a set of per-layer hybrid filters generated by a novel quantization method. They achieve significant energy savings and model size reduction while maintaining comparable accuracy. This approach is crucial for real-time applications on specialized hardware and can be generalized to other neural network architectures [21].

Every mobile phone offers the functionality of Short Messaging Services (SMS), and many people choose to use SMS for information retrieval. However, SMS texts can become noisy due to intentional or unintentional errors, necessitating the need to find the correct words to replace them. This paper efficiently denoises SMS terms by utilizing a ternary search tree to find matching prefix and suffix lengths, along with calculating a similarity score between the noisy tokens and the correct English words using the Longest Common Subsequence (LCS). It outperforms all of these previous methods [22]. The ternary logic also proves effective in the field of classification, offering efficiency, stability, and higher classification accuracy compared to some advanced methods, as demonstrated by experimental results [23]. There is a novel In-Memory Computing (IMC) architecture that includes configurable embedded Arithmetic Logic Units (ALUs) and can also be configured as a Ternary Content Addressable Memory (TCAM). This architecture performs well in Monte Carlo simulations, enhancing IMC parallelism, reducing energy consumption, and significantly decreasing calculation delays [24]. The ternary weight network exhibits better performance capabilities compared to its binary counterpart, achieving a higher model compression rate with fewer multiplication operations [25]. The Local Triangular-Ternary Pattern (LTriTP) is introduced as a novel feature descriptor for plant leaf disease detection, capable of efficiently extracting and representing features from leaf images. It achieves high classification accuracy for six disease classes of tomato leaf images, outperforming other renowned methods on the PlantVillage dataset [26].

III. Synthesis and Implication

A. The Mathematical Basis

From a computational perspective, in many computer applications, our goal is to reduce the number of calculations, thereby improving processing speed. A prime example of this is the application of ternary computing in data compression. Here, this study introduces a compression technique that combines absolute and relative positions, similar to one of the encoding methods used in transformers.

Let's consider a dataset, such as [10, 1] and [1, 24]. In this case, our objective is to merge these two matrices into one, with each element containing information from the corresponding element in the other matrix. For instance, 10 should encapsulate the information from 1 in the first matrix, while 1 should contain the information from 24 in the second matrix.

Initially, one might consider merging the second element as a decimal number, resulting in 10.1 and 1.24. However, this approach can introduce ambiguity because 10.1 can indeed represent the combination of 10 and 1. Due to the special nature of 0, 10.10 can also be abbreviated as 10.1. This means that using this decimal method, 10.1 might be misconstrued as the combination of 10 and 10, rather than 10 and 1. Thus, this method of decimal conversion is prone to ambiguity and is not advisable.

Additionally, the idea of omitting the comma when representing coordinates is considered. For instance, the coordinate (4, 5) can be directly represented as 45, omitting the comma. However, as coordinates become more complex, this method poses a challenge, making it difficult to discern the order of the numbers. For example, if the coordinate is (1234, 5678), our representation would be 12345678, leaving us uncertain whether it signifies (123, 45678) or (1234, 5678). So, this method also introduces ambiguity.

In more complex applications, involving both relative and absolute positions, we have adopted a method similar to positional encoding used in transformers, including basic trigonometry to encode positional information. For example, if we have a dataset like [1–5] and corresponding time indices like [11–15], we can use this encoding method to represent them for more efficient data processing.

The advantage of these compression methods lies in their efficient use of limited bits to represent specific numbers. Ternary systems can represent more digits compared to binary systems, potentially expediting the overall processing. However, it's essential to note that an increase in the number representation system doesn't necessarily mean an unlimited expansion of storage space. Therefore, further research is needed to find the optimal balance between processing speed and the number representation scheme to achieve the most efficient combination.

B. The Algorithms and Chip Design Inside the Computer

For the design of ternary circuitry, we can contemplate what kind of design is needed by first envisioning a specific application scenario. Let's take the currently popular field of AI as an example. If we ask the AI robot to help us create a painting, what would we need to do to accomplish this requirement?

First, we need to convert the analog signal of the sound waves representing our request into a digital electrical signal.

Secondly, we need to recognize and classify the electrical signals converted from sound waves so that we can understand the type of task associated with the request.

However, at this point, we encounter a challenging issue as our language contains many special words, such as homophonic words or polysemy words. Therefore, accurately recognizing the content of the request and understanding the meaning exactly becomes especially crucial. For example, in the following words, it's challenging to determine the specific word based solely on pronunciation: "Flour" and "Flower", "Two" "To" and "Too" or "Right" "Write" and "Rite". In such cases, we need to rely on the context in which the word is used to make the distinction. For instance, even though the words "two" and "too" sound similar in the sentences "There are two apples" and "There are too many apples" we can easily determine which word is being used in each of these contexts.

In addition, determining the meanings of polysemous words can also be done by observing the context. For example, in the contexts "Please turn on the light, it's too dark in here." and "Feathers are light, while bricks are heavy." the word "light" appears in both sentences, but its meanings are significantly different. This is where we only need to read the entire sentence to discern that in the first sentence, "light" refers to illumination, while in the second sentence, "light" refers to weight.

There are two different ways of encoding some information. One of them is one-hot coding, in which we use binary numbers and use "1" as the categorical class. In this case, we can have something like "00010", "00001", "00100", etc. Another way of doing this is to use real numbers instead of only having 1 as the categorical class, in which we can have the number "6" to represent a class. However, as we can calculate the distance between the classes, the encoding system should have some ways to encode one or more properties of the classes. For example, "cat" and "tiger" are both animals and can be encoded as numbers or vectors in ternary smaller than 10, while other non-animal classes should have very different numbering systems, like having negative numbers. This is also considered word embedding, which is widely used in many coding systems and machine-learning tasks.

We have successfully converted text into vectors using large language models. But how do we transform these text-based vectors into images? This is a relatively complex mapping process because the requests we receive describe and constrain the images we aim to generate from various perspectives. For example, if I want an image of a horse, the conditions "one" and "horse" are the limitations we need to consider, and thus, our generated image should fall within the boundaries defined by these two vectors.

Furthermore, images consist of numerous pixels, each composed of Red, Green, Blue, and Alpha channels (RGBA). This mapping process involves many addition and multiplication operations. To illustrate this, let's consider the example of "a horse," where these two vectors would be input into the four channels.

During this process, numerous parallel computations come into play. Graphics Processing Units (GPUs) are well-suited to handle the extensive addition and multiplication tasks required in the image generation phase, while AI units—Neutral Network Processing Units (NPUs) can handle the initial task of converting natural language into vectors, as mentioned earlier. Potential applications shall be mentioned in detail below in the next section.

C. Practical Application

Another representation system is known as the Residue Number System (RNS), which employs smaller numbers to represent larger ones. Unlike redundant numbers, RNS can significantly enhance the speed of algorithms in specific algorithm-intensive scenarios, particularly in signal processing applications. Additionally, RNS serves as a tool for exploring the limits of fast algorithm theory. RNS is a computational method that simplifies complex number calculations by converting them into a sequence of remainder numbers obtained by dividing the complex number by a series of co-prime numbers. This approach substantially accelerates calculation speed.

For instance, if we have two large numbers, say 39247499 and 41675189, we can divide them by 5 or 6 to reduce them to smaller numbers:

$$39247499 \div 5 = 7849499 \ldots..4 \tag{4}$$

$$41675189 \div 6 = 6945864 \ldots..5 \tag{5}$$

And then based on the Chinese Remainder Theorem, we can do addition for the remainders, which are 4 and 5.

$$4 + 5 = 9 \tag{6}$$

Finally, we need to convert it back to the result of the original operation between the two numbers, typically involving addition or multiplication, as division can be a bit tricky in this context.

$$9 ---> 39247499 + / \times 41675189 \tag{7}$$

This improvement has already been implemented in various chips, including Xilinx's (a chip manufacturer) FPGA (programmable chip) DSP (digital signal processing unit). It has been applied in FPGA as a DSP unit to enhance the performance of filters and operations like Fourier transforms.

D. Potential Development

The potential development of ternary computing in the field of computer science has brought both opportunities and challenges. Unlike the traditional binary system, ternary computing utilizes a base-3 numeral system consisting of 0, 1, and −1. This unique characteristic has several notable implications for the future of computer science, but it also presents numerous difficulties that are not easily overcome.

One potential advantage of ternary computing is its more efficient method of data representation. With three available states for each digit, ternary systems can represent information more compactly, potentially reducing storage requirements and enhancing data transmission speeds. This efficiency in data representation is particularly significant in applications where memory and bandwidth are critical factors. It holds great promise in areas such as information storage and data compression.

Additionally, ternary computing has garnered attention in quantum computing research. Quantum computers harness qubits that can exist in multiple states simultaneously, akin to the versatility of ternary digits. This feature may play a significant role in exploring the new field of quantum computing, potentially leading to breakthroughs in quantum algorithms and computational power.

However, the development of ternary computing units is not without its challenges. The primary difficulties lie in the hardware development of ternary logic gates, architectures of Central Processing Units (CPU), and various components. Although some previous research has been conducted in this field, bringing ternary systems to the level of binary systems in terms of logic gates, CPU architectures, and component synergy remains a formidable task. From a software perspective, transitioning from a binary to a ternary computing system would require significant modifications to the existing software ecosystem, including operating systems and programming languages. Additionally, it is uncertain whether major companies are willing to abandon their mature binary systems to develop a new and uncertain ternary system. Ensuring compatibility between the new ternary system and traditional binary-based software remains a major challenge. As ternary systems are unlikely to entirely replace binary systems, the coexistence of ternary and binary systems presents a serious issue that needs to be addressed.

Furthermore, adapting algorithms and software libraries originally designed for binary systems to work effectively with ternary data representation demands extensive reassessment and optimization. Establishing industry standards for ternary computing, including data formats, communication protocols, and hardware interfaces, is crucial for widespread adoption.

In conclusion, the potential of ternary computing in computer science holds promise for more efficient data representation and transformative applications in fields like quantum computing. However, a series of industry standards and challenges related to ternary systems remain to be explored and overcome. Despite the difficulties, the potential inherent in ternary systems cannot be ignored, and we believe that ternary systems can outperform binary systems in certain areas in the future.

IV. Conclusion

This study conducted a literature review that described the potential of ternary computers and corresponding algorithms in three aspects: the advantages of ternary over binary, the current applications of ternary in the field of computing, and the future development potential of ternary in the computer domain. This work filled a gap in this field, providing a relatively comprehensive literature review and supplementary explanations for an area that was not popular before.

The literature review of this study conducted is indeed not very detailed, and many areas require further explanation and more in-depth research. Unfortunately, there hasn't been much research on ternary systems in the field of computing. This is because binary computing systems are widely used and well-established, making ternary systems a relatively lesser-known area. The limited amount of literature on ternary systems made it difficult for us to create a comprehensive review.

Moreover, this review couldn't explore the theoretical aspects of ternary systems in great detail. This is because all known computer systems use binary, and even if there are ternary algorithms, they can't run on standard binary-based computers. This limitation prevented us from conducting many experiments related to ternary computing, leading to a lack of theoretical knowledge in this area.

Due to various constraints, both in our research and in the field as a whole, this study couldn't produce a complete literature review. However, we did our best with the resources available. We believe that as more researchers start studying ternary systems in the future, there will be more research in this area, and the related theoretical foundations will become stronger. This may allow us to create a more comprehensive literature review in the future.

Due to the lack of uniformity between algorithm development and transistor design and manufacturing, the inconsistency between algorithm maturity and hardware has hindered both experimental and theoretical progress. Therefore, we can conduct research from both hardware and algorithm perspectives simultaneously. Additionally, hardware optimization can also be explored from the angles of chemistry and physics.

Conflict of Interest

The author has claimed that no conflict of interest exists.

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