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Towards Artificial General Intelligence - A Survey of Hyperdimensional Computing and Vector Symbolic Architectures with Quantum Computing for Multivariate Predictions

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***Abstract*— To achieve true artificial intelligence would be to mimic the human brain. Some have espoused that current systems that we call AI today are nothing more than if-else statements. There are other arguments that state that indeed, the act of decision making itself is a bunch of nested if-else statements. However, we note that the human brain and through processes that are far more complicated than that has levels of cognition that far outweigh those of any machines that have been made today. While computing systems perform better at certain tasks than human beings do, they remain inherently specific. Human minds are generally creative and knowledge making entities. In this paper, we explore the current progress made towards achieving Artificial General Intelligence and look at it from the angle of Hyperdimensional Computing and Vector Symbolic Architectures both running with the power of quantum computing. We explain how the achievement of AGI will lead to a much more sustainable form of industrial development as has been touted through advancements towards the Fourth Industrial Revolution.**

Keywords—hyperdimensional computing, Vector Symbolic Architectures, quantum computing, artificial intelligence, machine leaning.

I. INTRODUCTION

In the endeavor to achieve the Sustainable Development Goals (SDGs) set by the United Nations to be realized by 2030, we see that the path forward still presents significant challenges. In the face of these challenges, technology's role as a transformative force cannot be overstated. As we move deeper into the Fourth Industrial Revolution, or Industry 4.0, the importance of automation and, more significantly, Artificial Intelligence (AI) is underscored[1].

Over millennia, humans have distinguished themselves from other creatures through tool creation, leveraging these tools to manipulate the environment and achieve desired outcomes. While it's true that other species use tools to some extent, the physicist David Deutsch proposes a compelling argument in his Constructor Theory: humans are unique in that they create knowledge and are therefore universal constructors[2]. This capability to construct knowledge and understand the "why" behind our actions allows us to enhance our tools consciously, facilitating our technological evolution.

Throughout history, humanity has traversed four significant phases of development concerning tool use. The term "Four Industrial Revolutions" coined by Klaus Schwab encapsulates this journey[3]. As described by E. G. Popkova, Y. V. Ragulina, and A. V. Bogoviz[4], the emergence of each industrial revolution is marked by an accumulation of novel technologies sufficiently impacting production processes. We now stand on the precipice of an AI-driven technological revolution, potentially shaping the Fourth Industrial Revolution. It can be argued that the key to this leap forward lies in the pursuit of Artificial General Intelligence (AGI). If AGI is achieved, we would create an artificial universal constructor[5], [6]. This could be a game-changer across all industrial sectors, accelerating sustainable development and providing transformative solutions to global challenges. Advancements in novel computing technologies, such as quantum computing, could potentially play a significant role in this endeavor. Quantum computers' superior computational capabilities, especially concerning large datasets and complex algorithms, could unlock new possibilities in AGI development and application. However, it is crucial to approach these developments holistically. The path to AGI not only requires breakthroughs in computational power but also hinges on multidisciplinary insights from neuroscience, cognitive science, psychology, and beyond. Our understanding of intelligence, learning, and cognition must expand alongside our technological advancements to ensure the effective and ethical application of AGI.

The hypothesis driving this research is that AGI is fundamental to the next industrial revolution. Through a deductive process, this paper seeks to explore this hypothesis, considering the multidimensional facets of AGI and the technological and ethical considerations it entails. Our aim is to contribute to the understanding and realization of AGI's potential, paving the way for a sustainable and equitable Fourth Industrial Revolution.

II. LITERATURE REVIEW

In this section, we look at key concepts that will lead us to a clear understanding of the overall technologies that are being explored. We dive into each topical area and try to ensure that groundwork is set for the final deductive conclusion study as to what the potential direction should be as concerns ensuing the achievement of the next industrial revolution. These technological revolutions have historically been driven by breakthroughs in our understanding and manipulation of the world around us. The next anticipated leap, signifying the Fourth Industrial Revolution, is expected to be fueled by advancements in artificial intelligence, particularly the development of Artificial General Intelligence or AGI.

A. *Artificial General Intellience – AGI*

Artificial Intelligence is the study in computer science about how computers can mimic human level intelligence. Unfortunately, it is the opinion of many researchers that Artificial Intelligence today is not so intelligent after all. This is because, despite current systems such as those in the branch of Machine Learning that make use of constructs such as artificial neurons and activation functions for reinforcement and ideas such as back propagation, the human neuron still outperforms these artificial systems by leaps and bounds because of the ability to process massive amounts of data in parallel and the ability of self-learning which lacks in modern AI systems. To further advance modern AI systems, the notion of Artificial General Intelligence or AGI was born. AGI aims to close the gaps in current systems such as those in machine learning with the missing features highlighted such as parallel computing and self-learning. As an example, the human brain has over 100 billion neurons with about 860 trillion connections among themselves[7]. In comparison, the most complex AI system build today has only 175 billion connections[8], very far from human level connections. Notably, further research is still ongoing in the field of AI with the goal of achieving AGI[9]. But the question would be, why would humanity want to achieve AGI? We will look at the driving forces in subsequent headings. It is also noted that AI will be an enabler for significant technological advancements in the coming years hence by extension, so will AGI. To achieve AGI, certain changes to the way computing is done might need to be adopted and that certainly starts with how we store and manipulate data more efficiently.

B. *Vector Symbolic Architectures*

Vector Symbolic Architectures (VSA), refer to the way symbols are stored or abstracted using high dimensional vectors so that they can be used for computations. In VSA, symbols are stored using Hyperdimensional Vectors and rules for how mathematical operations are applied to those symbols are generally the same as what would be understood in classical computing. The combination of Hyperdimensional Computing which we discuss in the next section and Vector Symbolic Architectures would entail that much more complex data can be worked with and manipulated in a much more efficient way than is currently done in most systems today. As an example, we might wish to abstract all the worlds characters using Hyperdimensional vectors with a standard format of say a vector with just 5 elements that each have a cardinality of 256, that would represent a potential total of over 33,554,432 or 256^5 symbols. All this information can be stored in a very tiny piece of space. We can then see that it is possible to abstract and save so much information representing as many objects and their iterations as we like, provided we have an efficient storage mechanism. For example, there could be one vector for just a green Apple, another one for a green apple with a bite at a hypothetical point, another for a green apple in a hand, another for a green apple in a hand of a human being etc. We could potentially create a datapoint for almost any observable phenomenon by reducing it into data and storing similar vectors together with methods of recreating complete objects from vectors of close similarity using mathematical operations[10] that are performed on those data points indicating their similarity and this is an important aspect in the field of Machine Learning. A question would then arise as to how mathematical operations would be performed using Vector Symbolic Architectures. Fortunately, this has already been covered in several works and there is ongoing work around more efficient ways of manipulating Hyperdimensional Vectors[11]–[13].

In summary,

- These technologies could be used to develop new artificial intelligence systems that are more powerful and efficient than current systems.
- They could also be used to develop new machine learning algorithms that are more accurate and scalable.
- Hyperdimensional Computing and Vector Symbolic Architectures could also be used to develop new methods for multivariate analysis that are more powerful and efficient than current methods.

The potential benefits of Hyperdimensional Computing and Vector Symbolic Architectures are significant, with the ability to revolutionize various fields, including artificial intelligence, machine learning, and multivariate analysis. These technologies not only contribute to advancements in Artificial General Intelligence (AGI) but also hold promise in enabling more powerful and efficient methods of multivariate analysis. By leveraging the capabilities of Hyperdimensional Computing and Vector Symbolic Architectures, researchers can analyze complex datasets with multiple variables simultaneously. Multivariate analysis plays a crucial role in domains such as data compression, machine learning, and AI. Therefore, the integration of Hyperdimensional Computing, Vector Symbolic Architectures, and Quantum Computing can facilitate advancements in multivariate analysis and drive further breakthroughs in these fields.

Having established the potential of Hyperdimensional Computing and Vector Symbolic Architectures in transforming a wide array of fields, it's essential we also delve into another promising advancement that holds the potential to further amplify these transformations - Quantum Computing. A revolutionary approach, Quantum Computing offers solutions that may supersede the capabilities of our current computing models, working synergistically with technologies like Hyperdimensional Computing to push the boundaries of artificial intelligence, machine learning, and multivariate analysis even further. After gaining an understanding of how VSA enables more complex data storage, we now explore how this data can be manipulated through Hyperdimensional Computing. Now that we have explained what is expected to be a new method of data abstraction and storage, we look at the way that the data can be manipulated.

C. *Hyperdimensional Computing*

Hyperdimensional computing is a recent area of research that aims to improve the way data is abstracted and computations done on that data by computing systems so as to take advantage of a multi-layered storage of data as compared to current models[10]. It can be thought of as a way to store and manipulate holographic level data because a single point in space may have an unlimited number of datapoints using the principal of near orthogonal vectors.

At this point, it might be helpful to visualize near orthogonal vectors in a more tangible way. Imagine standing at a bustling six-way intersection in a futuristic city. This isn't your conventional city – it expands not only in the horizontal plane but also vertically, offering an entirely new dimension. Each of the six roads leading from this intersection can be thought of as different vectors, leading to distinct destinations or data points. Now, imagine an upward path from this intersection that leads to another six-way junction in a higher layer of the city, providing an additional set of vectors or data points. Each intersection or vector isn't limited to the traditional two-dimensional right angles; instead, they intersect at angles that are near 90 degrees, or 'near orthogonal.' These intersections represent unique pieces of information, and their near-orthogonal nature signifies that they're nearly independent of each other.

Now, let's expand our thought experiment. Picture a sprawling cityscape with countless similar multidimensional intersections, each connecting near-orthogonal vectors. Each intersection or vector can hold different types of information, making the entire city a vast, interconnected dataset. This conceptual city is a lot like a hyperdimensional computing model. The city intersections are hyperdimensional vectors, and each road or direction is a dimension capable of holding a distinct data point.

As the term vector may be clearly understood as being a type of data that has both magnitude and direction, we can therefore conclude that near orthogonal vector points can be used to store a single type of information. In this case, we are not limited by the cardinality of the vector or by the number of individual data points that comprise the vector at the same point in for example the dimension of space because at that 3D point, there are many near orthogonal vectors of size N with cardinality of size M. Below is a mathematical representation of a Hyperdimensional Vector.

$$V_M = [v1, v2, ..., v_N]$$

where:

- V is the hyperdimensional vector.
- v_i is the i^{th} element of the vector.
- N is the size of the vector.
- M is the cardinality of the vector.

The elements of the vector can be any real number but for ease of computation they may be composed of binary digits. The cardinality of the vector is the number of individual values that the elements of the vector can take on. For example, if M = 2, then the elements of the vector can take on two individual values, such as 0 and 1. The equation of a hyperdimensional vector can be used to represent any type of data, such as text, images, and audio. It is a powerful tool that can be used in a variety of applications, such as data compression, machine learning, and artificial intelligence.

It might be important to state one very important distinction of Hyperdimensional Computing as compared with Classical Computing. HDC performs operations on vectors and outputs vectors while in Classical Computing, operations are performed on bits and bits are the output. There has been work in AI that has shown the efficiency in which HDC may be used to compare the similarity of languages or just identify a language by the structure and wording of a sentence. The easiest way would be to use Vector Symbolic Architecture to abstract say the letters of the English Alphabet into some arbitrary representation and to combine the individual vector elements of a word into another vector of the same format. This basically forms the building blocks of more complex data structures from base representations[10]. At this point, we can now note how easy it would be to achieve Multivariate Analysis with Hyperdimensional Computing and Vector Symbolic Architectures because it would be easy to collect as much information as possible from the environment using symbolic vectors. However, performing computations on HDC data structures may present challenges such as requiring computational power that may not be in mainstream use today. In the next heading below, we look at one such aspect of a novel approach towards computing that has the potential to solve problems with complex data structures such as the ones discussed in this paper.

D. *Unleashing the Potential of Quantum Computing*

Quantum Computing is a revolutionary approach towards classical computing that is generally well understood today. In the standard classical computing, data is represented by binary symbols called bits where a combination of bits form up a required symbol and mathematical operations are performed on that data using a computing model called the Von Neuman Architecture. To understand the difference between Quantum Computing and Classical Computing, we start by exploring how the current popular computing model works.

E. *The Von Neumann Architecture*

The Von Neumann architecture is computer architecture that was first described by John von Neumann in 1945. It is the most common type of computer architecture used today. The Von Neumann architecture consists of four main components:

1. Arithmetic logic unit (ALU): The ALU is responsible for performing arithmetic and logical operations on data.
2. Memory: Memory is used to store data and instructions.
3. Control unit (CU): The CU is responsible for fetching instructions from memory and executing them.
4. Input/output (I/O): I/O is used to communicate with the outside world.

The Von Neumann architecture is a stored-program architecture, which means that the instructions that are executed by the computer are stored in memory. This contrasts with earlier computers, which used a hardwired architecture, where the instructions were hardwired into the circuitry of the computer.

The Von Neumann architecture has several advantages, including:

- It is relatively simple to design and implement.
- It is flexible and can be used to implement a wide variety of programs.
- It is efficient in terms of space and time.

However, the Von Neumann architecture also has several disadvantages, including:

- It is not very scalable. It can be difficult to increase the performance of a Von Neumann architecture computer by simply adding more hardware.
- It is susceptible to a class of security vulnerabilities known as buffer overflows.
- It is not very energy efficient.

Despite its disadvantages, the Von Neumann architecture remains the most common type of computer architecture used today. This is because it is a well-understood and well-proven architecture that can implement a wide variety of programs.

F. A Leap into Quantum Computing

In contrast, Quantum computers are a type of computer that uses the principles of quantum mechanics to perform calculations. Quantum mechanics is a fundamental theory in physics that describes the behavior of matter and energy at the atomic and subatomic level. Quantum computers are based on the idea that quantum bits, or qubits, can be used to represent information. Qubits can be in a superposition of states, which means that they can represent both 0 and 1 at the same time. This allows quantum computers to perform calculations that are impossible for classical computers.

Quantum computers have the potential to revolutionize a wide range of fields, including cryptography, drug discovery, and materials science. Cryptography is the study of secure communication, and quantum computers could be used to break current encryption methods. Drug discovery is the process of finding new drugs to treat diseases, and quantum computers could be used to simulate the behavior of molecules, which could help to identify new drug targets. Materials science is the study of the properties of materials, and quantum computers could be used to design new materials with desired properties.

Quantum computers are still in their early stages of development, but they have the potential to have a major impact on the world. As quantum computers become more powerful, they will be able to solve problems that are currently impossible for classical computers. This could lead to new discoveries and innovations in a wide range of fields.

Below are some of the potential benefits and potential outcomes of quantum computers:

- Breaking current encryption methods: Quantum computers could be used to break current encryption methods, which could have a major impact on cybersecurity. Fortunately, there is research in this filed that will prepare the world for much more advanced quantum-resistant encryption standards.
- Design new materials: Quantum computers could be used to design new materials with desired properties, currently, running massive simulations on classical computers for material discovery is heavily compute intensive and quantum computer would make this process more efficient. This could have a major impact on a wide range of industries, such as energy, manufacturing, and transportation.
- Solving complex problems: Quantum computers could be used to solve complex problems that are currently impossible for classical computers, such as simulating the behavior of the universe or finding the optimal solution to a complex optimization problem. Interesting experiments could be conducted such as the application of Chaos Theory to standard experiments.

It is important to note that the development of quantum computers is a rapidly evolving field making it difficult to predict what the future might look like. However, the potential benefits of quantum computers are significant, and they have the potential to revolutionize a wide range of fields[14]–[16].

G. Quantum Computing Architecture: A New Approach

Quantum computers do not use the Von Neumann architecture because they do not use the same type of logic as classical computers. Quantum computers use quantum logic, which is based on the principles of quantum mechanics. Quantum logic is very different from classical logic, and it does not allow for the same type of instructions that are used in classical computers. As a result, quantum computers use a different type of architecture that is specifically designed for quantum logic. This architecture is called the quantum gate model. The quantum gate model is a very different architecture from the Von Neumann architecture, and it is not compatible with classical computers.

The quantum gate model is a very powerful architecture, and it can perform calculations that are impossible for classical computers. However, it is also a very complex architecture, and it is difficult to implement. As a result, quantum computers are still in their early stages of development, and they are not yet widely available.

H. The Application of Quantum Computers to AGI

Quantum computers have the potential to revolutionize artificial intelligence (AI) by enabling new AI algorithms and applications that are impossible with classical computers.

Some of the potential applications of quantum computers in AI include:

- Machine learning: Quantum computers could be used to train machine learning models much faster than classical computers. This could lead to the development of new machine learning algorithms that are more accurate and efficient.
- Natural language processing: Quantum computers could be used to develop new natural language

processing (NLP) algorithms that can understand and process human language more effectively. This could lead to the development of new NLP applications, such as chatbots and machine translation systems.

- Computer vision: Quantum computers could be used to develop new computer vision algorithms that can see and understand the world more effectively. This could lead to the development of new computer vision applications, such as self-driving cars and medical imaging systems.
- Cryptography: Quantum computers could be used to break current encryption methods, which could have a major impact on cybersecurity.
- Drug discovery: Quantum computers could be used to simulate the behavior of molecules, which could help to identify new drug targets and develop new drugs.
- Materials science: Quantum computers could be used to design new materials with desired properties, which could have a major impact on a wide range of industries, such as energy, manufacturing, and transportation.

As concerns AGI, Quantum Computers could be used to perform mathematical operations of huge datasets such as those described in Hyperdimensional Computing at fractions of seconds as compared to Classical Computers. This would make the development of much more complex algorithms possible opening the way for simulating much more complex environments as may be required to achieve AGI. As previously highlighted, to achieve AGI would be to simulate the human brain. However, given the massive parallel processing of the human brain, popular computing in its current state may not be able to simulate the human brain. It must also be noted that either than new computing models, there may still be need further understand concepts associated with the human brain such as intelligence, learning, and cognition, and the development of new AI algorithms and architectures that can replicate the breadth and depth of human cognitive abilities. As an example of the impact of Quantum Computers on AI, it is worth noting that the Classical Travelling Salesperson problem can be solved in a fraction of a second for very large number of nodes as compared to the time taken on a Classical Computer.

In the next section below, we now look at where all the technologies discussed previously may be applied in such a way as to assist in sustainable industrial development.

I. The Fourth Industrial Revolution

Humanity has been through 4 industrial revolutions, and these are briefly explained. The First Industrial Revolution is generally thought to have included developments such as Cast Iron, Steam engines and the Textile Industry, this is widely believed to have occurred between the 18^{th} to early 19^{th} centuries. These innovations replaced a lot of manual labour and required the development of infrastructure to support the new industries.

The Second Industrial Revolution brought about innovations such as Chemical Engineering, the Railroad to support mass transportation, the production of Steel and the emergence of electricity. This obviously improved upon feature of the previous revolution and brought about massive economic growth. It can also be noted that there was some form of disruption to the traditional way of doing business. This happened in the late 19^{th} to early 20^{th} century.

The Third Industrial Revolution saw the proliferation of technologies such as renewable energy, digital technologies, and the expansion of business networks across the globe. It also saw the development of global infrastructure such as fiber optic cables, global networks, satellites, and the Internet. Once again, the traditional methods of doing business were disrupted but the world saw massive economic growth.

We are now amid the Fourth Industrial Revolution, and it can already be noted what kind of technological breakthroughs are expected to be rolled out on a global scale. It is expected in the 21^{st} Century and technologies that are expected to be in widespread use are Internet of Things, Robotics, and automation in Industry. It can be noted that to achieve robotics and industrial automation will require the use of Artificial Intelligence and therefore may lead to a significant reduction in human intervention in the production processes. The study of AI and AGI therefore becomes fundamental towards the goals of Industry 4.0. If nation states do not prepare themselves for this, they risk their citizens not benefiting from the economic growth that is expected as Industry 4.0 rolls out and the risk of potentially not achieving the Sustainable Development Goals. A careful look at the SDG’s indicate that technology plays a fundamental role in their attainment. A lot of work has been done that links the use and development of technological solutions towards achieving sustainability and therefore assisting efforts such as alleviating Climate Change and therefore protecting the environment for generations to come.

III. Research Questions

1. Are there any perceived benefits when Hyperdimensional Computing and Vector Symbolic Architectures are applied to the field of Quantum Computing?
2. Can the conclusions raised in (1) above assist in the realization of much more advanced AI systems such as Artificial General Intelligence?
3. Are there areas of improvement that can be highlighted towards the achievement of AGI?
4. Is there research that shows the potential benefits of AGI towards a much more sustainable global economy?

IV. RESEARCH OBJECTIVES

1. To conduct systematic literature review to ascertain the benefits of Hyperdimensional Computing and Vector Symbolic Architectures and Quantum Computing working in tandem.

2. To formulate an understanding as to the benefits of the results in (1) to research in Artificial General Intelligence
3. To suggest areas of improvement to the study and advancement of AGI
4. To list significant research contributions highlighting the benefits of AGI towards a sustainable global economy.

V. Methodology

This research primarily employed a systematic literature review as the main method. We targeted academic sources such as peer-reviewed papers, books, academic editorials, and conference proceedings, all published within the last 5 years. Our focus on recent sources was motivated by the rapid advancements in the realm of AGI and the need for the most contemporary insights. Older resources were excluded due to potential obsoleteness and the likelihood of their findings having been referenced by newer research.

A. Inclusion Criteria

We looked at papers that were written in the last 5 years because there has been considerable research in the realm of AGI within that timeframe and the older the research, it might be likely that the results are outdated or have been referenced by newer researchers. We also used sources from books, academic editorials, conferences, and journals.

B. Exclusion Criteria

All sources that are not peer reviewed or have not been presented before attendants for critiquing. Also, all sources that are older than 5 years.

C. Search Phrase synthesis

Coming up with the search phrases in Table 3 above started by ensuring that there are sufficient articles from the keywords of this topic that were obtained from the title of the article. We wanted to see if each of the key items had research done in the last 5 years. Specifically, the keywords were Hyperdimensional Computing (HDC), Vector Symbolic Architectures (VSA), Quantum Computing and Artificial General Intelligence (AGI). The scoping was meant to ensure that there are enough resources available on the search databases for each of these topics. Specifically, we used Microsoft Bing, Google Search and Google Scholar. The idea was to eventually form compound searches from each of these topics and to gain an overall understanding as to the extent of research conducted in each of these separate fields. It should be noted that we were here also looking for articles that fitted the inclusion criteria and did not get articles that fell within the exclusion criteria within the scoping exercise. For that, parameters of the inclusion and exclusion criteria were added to the advanced search options of Google and Microsoft Bing while a filter of the year published to ensure articles are no older than 5 years was added to Google Scholar. The searched were conducted between April and June 2023. Search results highlights were obtained from the first page of the results only. Within the scope of Google Scholar and Microsoft Bing, the parameters in Table 1 below indicate what was added at the end of the search string to narrow down the search to fit the timeframe of the inclusion and exclusion criteria. We adjusted the keywords in each case to maximise the output of the results. Below in Table 2 and Table 3 are examples of the search for each of the items and adjustments to parameters made shown as Parameter 01, Parameter 02 and Parameter 03. We continue to adjust the parameter in the source keyword until we just have one remaining. The adjustments were done by simple elimination of subsequent words and all combinations of the keyword parameters possible. In the example in Table 1 below, some combinations such as *"source: academic editorial, book"* are not shown but were also used. Calculating the number of combinations of the keywords possible can be done with the formula below.

$C(n, k) = n! / [k!(n-k)!]$, where:

- n! denotes the factorial of n (the product of all positive integers up to n),
- C(n, k) denotes the number of combinations of n items taken k at a time.

Hence for our 4-word source keyword in Google, we had 15 combinations.

Table 1 - Keyword Search String Formulation - Google

Key Words/Phrases	***Parameter 01 - Google***	***Parameter 02 - Google***	***Parameter 03 - Google***
Hyperdimensional Computing	after:2018-01-01 book OR conference article OR journal OR academic editorial	date:2018-01-01 conference article OR journal OR academic editorial	date:2018-01- journal OR academic editorial

Table 2 - Keyword Search String Formulation - Bing

Key Words/Phrases	***Parameter 01 - Bing***	***Parameter 02 - Bing***	***Parameter 03 - Bing***
Hyperdimensional Computing	Scholarly articles		

Below are two examples of the compound search for Hyperdimensional Computing on both Google and Bing. It must be noted that Bing search has very little in the way of keywords for narrowing down search results and refining them hence there was no need for other parameters.

- Bing – "Hyperdimensional Computing" Scholarly Articles
- Google – "hyperdimensional computing" after:2018-01-01 book, conference article, journal, academic editorial.

Next was to combine the keywords into compound search phrases as discussed in the next section.

D. Search Phrases

The search for relevant literature was conducted using Google Scholar, Microsoft Bing, and the Google search engine. To ensure comprehensive coverage, we formulated compound search phrases with various combinations of the following three keywords:

- Hyperdimensional Computing (HDC)
- Vector Symbolic Architectures (VSA)
- Quantum Computing
- Artificial General Intelligence

Sample search phrases included:

- Hyperdimensional Computing and Vector Symbolic Architectures with Quantum Computing
- How Quantum Computing can be applied to Hyperdimensional Computing and Vector Symbolic Architectures
- Benefits of Quantum Computing to Hyperdimensional Computing and Vector Symbolic Architectures

The target was to identify at least 100 papers addressing the subjects of interest. All sources were then analyzed based on citation ranking, relevance to the research questions, and adherence to the inclusion and exclusion criteria.

Finally, we employed deductive reasoning to draw conclusions from the analyzed resources. The deductions provided valuable insights for the achievement of the research objectives.

Table 3 below is a summary of the search phrases that were used for each of the four questions posed. Note that compound search phrases followed the examples highlighted for the individual topical areas in Table 1 and Table 2 above and followed the same methodology when searching for the results. However, for the final search phrases, we narrowed the results down to only peer reviewed articles that addressed our hypothesis.

TABLE 3 - SEARCH PHRASES

Research Question	***Phrases***	***Search Questions***
Are there any perceived benefits when Hyperdimensional Computing and Vector Symbolic Architectures are applied to the field of Quantum Computing?	Hyperdimensional Computing, Vector Symbolic Architectures, Quantum Computing	1. What are the benefits of using Hyperdimensional Computing and Vector Symbolic Analysis in Quantum Computing? 2. How can Hyperdimensional Computing and Vector Symbolic Analysis be used to improve the performance of Quantum Computing? 3. What are the challenges of using Hyperdimensional Computing and Vector Symbolic Analysis in Quantum Computing?
Can the conclusions raised in (1) above assist in the realization of much more advanced AI systems such as Artificial General Intelligence?	Artificial General Intelligence (AGI) Hyperdimensional Computing Vector Symbolic Analysis	1. How can Hyperdimensional Computing and Vector Symbolic Analysis be used to develop AGI? 2. What are the challenges of using Hyperdimensional Computing and Vector Symbolic Analysis to develop AGI? 3. What are the potential benefits of using Hyperdimensional Computing and Vector Symbolic Analysis to develop AGI?
Are there areas of improvement that can be highlighted towards the achievement of AGI?	Artificial General Intelligence (AGI) Areas of improvement	1. What are the areas of improvement that need to be addressed in order to achieve AGI? 2. What are the challenges of achieving AGI? 3. What are the potential benefits of achieving AGI?
Is there research that shows the potential benefits of AGI towards a much more sustainable global economy?	Artificial General Intelligence (AGI) Sustainable global economy	1. What are the potential benefits of AGI for a more sustainable global economy? 2. What are the challenges of using AGI for a more sustainable global economy? 3. What is the research that shows the potential benefits of AGI for a more sustainable global economy?

Below we discuss the methods used to synthesize the search phrases.

VI. RESULTS

For the search phrase scoping, the following in Table 4 are the results we obtained.

Table 4 - Results of Key Words Search

Key Words/Phrases	***Google Results Count***	***Bing Results Count***	***Google Scholar Results Count***
Hyperdimensional Computing	1,330	636,000	1,530
Vector Symbolic Architectures	318	77,500	638
Quantum Computing	177,000	255,000	307,000
Artificial General intelligence	15,500	1,120,000	19,700

We noted that Google provided a much more refined method of search than did Bing which was a bit broader and had fewer keywords to assist in targeted results. The search results on Google returned a much more refined and targeted number of articles while if the parameters were reduced to a specific combination such as journals and conference articles, we had a smaller result set indicating that the fine-tuning was working just fine. Google Scholar had more results than Bing for searches performed there as that site is specially suited to index only scholarly article hence there was no need to refine the searches with keywords and parameters. Only the search phrases in quotation marks, to signal that we were interested in the exact phrase, were used. We recorded the maximum results found for each combination of keywords on each of the search databases. These differences in the operations of the search engines could be attributed to the differences in classification of the sources of information and the way the sites are indexed. Overall, we have concluded that Google and Google Scholar had the best results. The search of each of these keywords provided valuable insight in the scale of research in these fields which in this case indicated that research is still quite novel. The next phase was to combine each of these keywords into compound terms involving each of the concepts discussed. There isn't considerable research conducted in each of the specific areas of the topic except for Quantum Computing which has a sizeable number of research articles published. but the next question was, is there sufficient research in a combination of each of these separate topics leading towards AGI?

We were looking for at least 100 papers that address the subject of this paper with the compound search terms highlighted. However, we note that since the field is still quite novel, there is still a lot of research that is currently ongoing. Nonetheless, we summarize the available papers based on the key thematic areas of the systematic review that was carried out. Table 5 below is a table that summarizes the findings.

From the earlier search on keyword synthesis, we concluded that the best search engine to use for the final searches would be Google Scholar as it had provided more results than the refined Google search and the broader Bing search and would therefore also provide mostly peer reviewed work.

TABLE 5 - THEMATIC AREA RESULTS

Thematic Area	***Found References***	***Papers***
HDC and VSA as applied to computing, Quantum Computing	3	[17]–[19]
Benefits of HDC and Quantum Computing to AGI	3	[13], [19], [20]
Areas of improvement in advacement of AGI	1	[7]
Benefits of AGI to sustainable global economy	2	[1], [21]

There was only a total of 9 papers that were identified as concerns the topical areas concerning this research, that is from compound phrases of the individual concepts discussed. This could be attributed to the few numbers of countries that have active quantum computers or the few numbers of researchers or institutions that are actively engaged in the research of AGI. While there are several research papers on the individual concepts, it appears that there is very little research focusing on how to apply each of the concepts highlighted in the paper to the attainment of AGI. It is the opinion of the authors that more work in and around the area of AGI and quantum computing needs to be undertaken to ensure that those technologies are readily available to a large number of individuals for the benefits of all as it has been noted that there are more benefits when AI is used to assist in achieving the Sustainable Development Goals[1], [22].

We can deduce that to propel humanity into the 4^{th} Industrial Revolution and to achieve sustainable development, several technologies will have to come to maturity. Key among those technologies will be Artificial General Intelligence, novel methods of storing and manipulating data and Quantum Computing. It is therefore critically important that more research in these areas is performed with a goal towards a much more inclusive future and one where technology becomes a way of life.

Based on the limited number of relevant studies identified in our systematic review, we have observed a substantial research gap in the intersection of Hyperdimensional Computing, Vector Symbolic Architectures, Quantum Computing, and their applications towards the advancement of Artificial General Intelligence. This scarcity of peer-reviewed literature emphasizes the novelty of this multidisciplinary area, as well as the complexity of the topics at hand. We observed that research in Quantum Computing has outpaced that in the other topical areas of Hyperdimensional Computing, Vector Symbolic Architecture and Artificial General Intelligence. This could signify why there is little research in the concepts discussed towards the attainment of AGI. We have concluded that this is a viable area of research that holds much promise and requires more researchers to jump in[23].

A. *Deductive Reasoning*

We hypothesized that AGI can be achieved and to get to that point, fundamental methods of computing will have to change. Through literature, we suggest Hyperdimensional Computing and Vector Symbolic Architectures. That statement can then be broken up into some individual objectives which we had looked at. Those individual concepts being HDC, VSA and Quantum computing. Research on these topics concluded that indeed they can be used to formulate new computing frameworks that may be required to achieve AGI as the current computing models may not be sufficient. We then went on to further assess whether there is active research incorporating the ideas of this hypothesis that HDC, VSA and Quantum Computing are necessary for the attainment of AGI and literature has also shown that some scholars do agree. We then further went on the consider whether AI and indeed AGI would have an impact of a sustainable global economy and research has shown that AI and by extension AGI, is quite critical towards the attainment of most of the sustainable development goals[1]. However, there are not many scholars that have delved into this field. What is important to note is that this is one area worth exploring.

B. *Conclusion*

Our original aim was to analyze approximately 100 papers that explore the use of Hyperdimensional Computing and Vector Symbolic Architectures to achieve AGI with a bias to Quantum Computing. However, we were able to identify only 9 relevant papers that directly addressed our research questions. Despite the small number of papers found, this in no way invalidates the aim of the study as it has been observed that there has been systematic review with as small as only 2 studies reviewed. It is also generally accepted that there is generally no set standard as to the minimum required number of articles in Systematic Reviews[24]. This shortfall from our target highlights the need for further research in this field. It also suggests that there are opportunities for more in-depth study and novel contributions, particularly in the application of these computing paradigms to the advancement of AGI, and their potential benefits for a more sustainable global economy.

This research gap is especially significant given the transformative potential of AGI and quantum computing for numerous sectors and their potential role in the Fourth Industrial Revolution. Moreover, as indicated in our research objectives, these technologies could have profound implications for achieving the Sustainable Development Goals.

While this research gap presents a limitation in terms of the conclusions we can draw from our current analysis, it also provides a clear direction for future research. We hope our work serves as a steppingstone for more comprehensive studies in these areas and catalyzes further exploration and discourse in the global research community.

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