vidya
Progress Through Education

DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

VISION

"TO BE A CENTRE OF EXCELLENCE IN ELECTRONICS AND COMMUNICATION ENGINEERING THROUGH VALUE-BASED EDUCATION AND RESEARCH"

MISSION

M1: *TO PROVIDE STUDENTS STATE-OF-THE-ART ACADEMIC AMBIANCE FOR QUALITY EDUCATION.*

M2: *FACILITATE INTERDISCIPLINARY LEARNING, INDUSTRY INTERACTIONS AND RESEARCH INITIATIVES FOR LONG TERM CAREER DEVELOPMENT GOALS.*

M3: *TO EDUCATE AND MENTOR STUDENTS ON PROFESSIONAL RESPONSIBILITIES, ETHICAL VALUES AND LIFELONG LEARNING.*

AYYALASOMAYAJULA LALITHA

Ayyalasomayajula Lalitha, India's first female engineer, defied societal norms with resilience and determination. Widowed at 15, she pursued engineering at CEG, graduating in 1943 as the only woman in her class. Contributing to projects like the Bhakra Nangal Dam, she broke barriers in a male-dominated field. Her legacy remains a symbol of perseverance and self-belief.

" *Lalitha's legacy stands as an enduring symbol of perseverance, resilience, and the courage to challenge conventions.* "

Principal's Message

It is a matter of great pride and satisfaction to present the fifth edition of WISSEN 5.0, the technical magazine of the Department of Electronics & Communication. This magazine stands as a testament to the department's unwavering commitment to academic excellence, skill development, and innovation.

The Department of Electronics & Communication has made tremendous progress in academics, research, technical advancements, and extracurricular engagements. I am confident that this issue of the magazine will showcase the accomplishments and talents of the students and will also serve as a reference document for staff, students, and those interested in technical education and technology-based activities.

I extend my heartfelt congratulations to the Head of the Department, faculty members, and students for their dedicated efforts in bringing out this edition. The active participation of students in co-curricular and extracurricular activities, along with their dedication to academics, is truly commendable. Their enthusiasm and commitment to knowledge-sharing will undoubtedly shape them into well-rounded professionals, ready to contribute to the ever-evolving technological landscape.

I wish WISSEN 5.0 great success and hope it continues to inspire and enlighten its readers with every edition.

Happy Reading.

_____

Regards,

Dr. Sunitha C
Principal
Vidya Academy of Science & Technology

HoD's Message

It is with immense pride and enthusiasm that I present the fifth edition of our technical magazine, Wissen 5.0. This magazine serves as a platform to showcase the relentless pursuit of knowledge, innovation, and technical excellence in the field of Electronics and Communication Engineering (ECE).

Our department has always been at the forefront of academic and research advancements, fostering a culture of creativity, collaboration, and continuous learning. The contributions of our talented faculty and students in emerging technologies, research, and projects reflect their commitment to shaping the future of engineering. Wissen 5.0 is a true representation of their hard work and passion.

I extend my heartfelt congratulations to the editorial team and all contributors for their dedication in bringing this edition to life. A special note of gratitude to our management and directors for their unwavering support in all our endeavours.

Let us continue to push the boundaries of contribution and strive for excellence. Wishing you an insightful and inspiring read!

Warm regards,

Dr. S. Swapna Kumar
Professor and Head
Department of ECE
Vidya Academy of Science & Technology

Editor's Message

It is with great enthusiasm that I present the fifth edition of Wissen 5.0, a platform that brings together insightful ideas, technological advancements, and innovative contributions in the field of Electronics and Communication Engineering. This magazine reflects the dedication, creativity, and passion of our academic community in exploring the ever-evolving world of technology.

I extend my sincere gratitude to the HoD of the ECE Department and the college authorities for their invaluable support in the successful design and publication of this edition. A special appreciation goes to the team of writers, editors, designers, and contributors whose hard work and commitment have made this magazine a reality. Your efforts continue to inspire and drive excellence.

I hope Wissen 5.0 ignites curiosity, fosters learning, and provides inspiration for all readers.

Happy reading!

Warm regards,

Remya K R
Department of ECE
Vidya Academy of Science & Technology

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ARTIFICIAL INTELLIGENCE & MACHINE LEARNING

ARTIFICIAL INTELLIGENCE IN IoT BASED WIRELESS SENSOR NETWORKS

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Wireless sensor networks (WSNs) represent an advanced technology driven by recent developments in miniaturized manufacturing by integrating multiple electronic components into compact structures. These networks serve as transformative tools for monitoring and data collection in diverse environments.
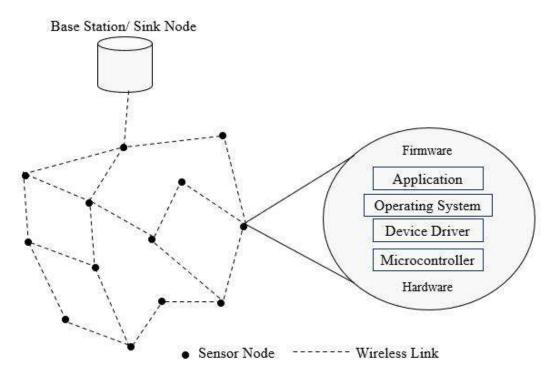
Fig. 1: Basic structure of a Wireless Sensor Node (Narwarla and Mazumdar, 2023)

In a WSN, sensor nodes communicate with a central gateway and transmit information about their surroundings, as shown in Figure 1. Each node is equipped with a small processor, various sensing devices such as motion, temperature, or sound sensors, and a wireless radio. . While nodes consist of many small, spatially dispersed, battery-powered sensor nodes capable of sensing, processing and communicating wirelessly. These nodes can temporarily store sensor data and perform calculations with it. [1]. These networks play a key role in the development of the Internet of Things (IoT) and are widely used in areas such as environmental monitoring, healthcare, industrial automation and smart city development. These networks vary in technical structure, with some types being highly adaptable, fault-tolerant and responsive, as well as compact in design. The potential of WSNs extends further into urban administration and military applications, where their capabilities hold significant promise [2]. WSN designers face several common challenges, including (1) security, (2) data reliability, (3) data aggregation, (4) event scheduling, (5) energy-efficient routing, (6) node clustering, (7) errors. detection and (8) localization [3].

Introduced in the late 1950s as a method for artificial intelligence (AI) and machine learning (ML). Today, a revolutionary approach called AI and ML is emerging as the foundation for fully automated IoT applications. Machine learning, a subset of artificial intelligence, allows computer algorithms to learn independently by improving their performance based on past experience. AI and ML techniques have huge potential to effectively manage the automated operation of Internet of Things (IoT) nodes deployed in various applications. Since then, he has focused on more robust and computationally feasible algorithms. Over the past decade, ML techniques have been widely applied to various tasks, including density estimation, regression, and classification, in areas such as (1) spam detection, (2) speech recognition, (3) bioinformatics, (4) advertising, (5) fraud detection and (6) computer vision [3]. IoT applications include areas such as intelligent traffic monitoring, smart grids, efficient waste management, precision agriculture and advanced healthcare systems. [4].

A WSN is a dynamic system that constantly evolves over time, which greatly affects its operation and requirements. These changes may include shifts in mission or functionality at various levels, changes in the static or dynamic composition of nodes, changes in power consumption patterns for nodes and for the entire network, and the potential loss or failure of certain nodes. In addition, temporary interruptions can disrupt individual nodes, clusters of nodes or parts of the network and affect their ability to function within the usual framework [1]. WSNs to gain significantly higher levels of computational intelligence. The computational capabilities of ANNs are well documented in a wide variety of problem domains, enabling them to address many key problems in computing. This makes ANN a highly adaptable and powerful tool for various problem-solving applications. These aspects include, in particular, the ability of the architecture to scale according to the size of the problem, the computational complexity in space and time, and the complexity of communication or messaging [1].

Preliminaries in Machine Learning for WSN-IoT

Machine learning is an area of artificial intelligence (AI) that provides systems with the ability to automatically learn and improve based on previous experience without being explicitly programmed. His goal is to develop new computer programs that can access data and use it to learn for themselves. Machine learning (ML) for WSNs means learning sensor nodes and networks from their past experiences and making predictions based on them. ML for WSN and IoT primer covers the basic concepts and techniques necessary to apply ML to WSN-IoT applications. These preliminary tests include a basic understanding of supervised, unsupervised, and reinforcement learning, as each serves different IoT needs such as classification, anomaly detection, and predictive analytics.

Wireless Sensor Networks Based Internet of Things (WSN-IoT)

WSN-IoT end nodes using the IEEE 802.15.4 standard offer a maximum data rate of 250 kbps. These nodes are typically powered by two AA batteries (1.5 V, 1000 mAh) with the gateway connected to the mains. In terms of machine learning, the data flow in a WSN-IoT system takes place in several steps as shown in Figure 2, (1) acquiring data from sensors, (2) transmitting data from end nodes to the gateway, (3) aggregating data into gateways, (4) receiving, storing, and retrieving data in the cloud, (5) data analysis, (6) sensor node connectivity, and (7) data security tasks. In summary, ML techniques can be used in WSN-IoT to solve problems related to location, coverage, connectivity, MAC and routing layers, data aggregation, error detection, event monitoring, power restoration, quality of service (QoS), and network security.
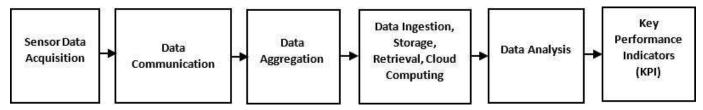
Fig. 2: Data flow in a typical WSN-IoT application. (Himanshu Sharma et.al. 2021)

Figure 3 presents a general flowchart illustrating the process of machine learning, model testing, and WSN action within WSN-IoT.
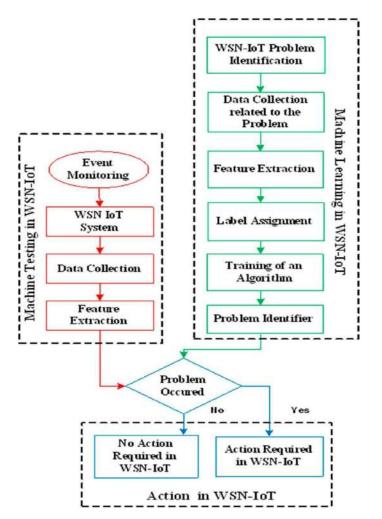
Fig. 3: Process flow-chart of machine learning in WSN-IoT. (Himanshu Sharma et.al. 2021)

Training Process

The training process in machine learning is a sequence of steps designed to teach a model how to make predictions or decisions based on data. It begins with data collection and preparation, where a representative set of data is collected, cleaned and processed to increase accuracy. Next, feature extraction and selection will focus on identifying and selecting key data attributes that reveal patterns, which will

help streamline the model and improve its focus. For example, data about image format properties such as colors, pixels, brightness, and contrast are derived from the entire image database. The extracted features are categorized based on the requirements of the machine learning process. A set of training examples is used to guide the algorithms, allowing them to learn or improve. Subsequently, these algorithms are trained and optimized according to the identified data patterns.

Testing Process

The testing process in machine learning involves evaluating the performance of a trained model on a new, unseen data set to assess its accuracy and generalization. This step ensures that the model can make reliable predictions outside of the training environment. During testing, the model processes this fresh data and produces outputs that are then compared to actual results to calculate various performance metrics. These metrics help identify any issues, such as overfitting or underfitting, and provide insight into the effectiveness of the model in real-world applications. In real life, unknown data is taken as input and features are extracted from it. These extracted features are applied to the trained algorithm. The output of the trained algorithm is classified as data prediction [4].

The benefits and shortcomings of utilizing ML/DL techniques over traditional approaches

Machine learning (ML) and deep learning (DL) techniques offer several advantages over traditional approaches. These include improved accuracy, the ability to process large data sets, adaptability to complex and non-linear patterns, and a reduced need for manual feature engineering. ML/DL models also improve automation in decision-making processes and can improve over time with more data. However, there are also limitations. ML/DL methods often require significant computational resources and large labeled datasets for effective training. They can be complex and more difficult to interpret, presenting problems of explainability. In addition, these models are prone to overfitting if not properly managed and can require significant time and expertise to tune and optimize. ML approaches, especially DL techniques, have been effectively applied to WSN applications including dimensionality reduction, classification, forecasting, feature extraction, and clustering. Advantages of using ML approaches for WSNs include reduced computational complexity, improved accuracy, extended network lifetime, and higher energy efficiency. Figure 4 shows results from a survey of ML-based algorithms on WSN approaches. The advantages identified for ML methods are improved accuracy and longer network lifetime. However, training times and the need for large datasets are often cited as disadvantages in studies.

Since both extended training periods and large datasets require significant amounts of energy, achieving a balance between energy efficiency and accuracy is crucial for resource-constrained WSNs. Additionally, these papers point to the difficulty of selecting appropriate ML approaches for WSNs as another challenge [3].

Methodology

- Data Collection and Processing: Sensors collect data that is cleaned and pre-processed.
- Model Training and Deployment: Machine learning models are trained on historical data and deployed at the edge or cloud.
- Optimization and Feedback: Models are improved based on feedback to improve accuracy and reduce power consumption.
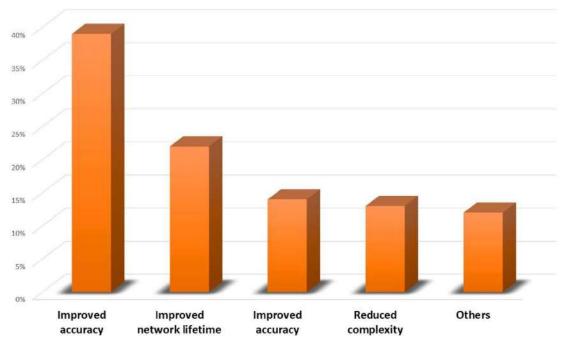
Fig. 4: Effect of ML-based algorithms on WSN's performance. (Salim El Khediri et.al. 2023)

Mathematical Functions:

1. Predictive Modeling: Regression for forecasting, e.g., $\sum$.
2. Energy Optimization: Minimizes energy consumption, $\sum$.
3. Anomaly Detection: Distance functions to identify outliers.
4. Classification: Neural networks or SVMs for decision-making.

Design:

1. Sensing Layer: Collects data through low-power sensors.
2. Network Layer: Transmits data using protocols like BLE and LoRaWAN.
3. AI Processing Layer: Analyzes data and makes autonomous decisions either on the edge or cloud.

This structured approach enables effective integration of AI, optimization of WSN functionality, and enhancement of various applications.

Performance Analysis

The statistical values represent the level of AI performance in IoT-based WSNs. This may vary depending on the application, design, and type of algorithms and classifications used. Here are some important statistical measurements and typical values that can be used to evaluate performance guidelines.

  i. Accuracy: AI models can achieve accuracy rates ranging from 80% to over 95% depending on the complexity of the task and the quality of the data.
 ii. Precision: Precision varies widely, but values greater than 75% are often considered acceptable in many IoT application tasks.
iii. Recall (Sensitivity): In applications where missing detection is critical (e.g., health monitoring), recall rates are often set above 85%.

DESIGN AUTOMATION AND IMPLEMENTATION OF MACHINE LEARNING CLASSIFIER CHIPS

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Abstract

This paper introduces an innovative framework designed to automate the process of creating a trained-classifier integrated circuit directly from a dataset. Accepting data in comma-separated values (CSV) format, the framework processes and generates a trained model through a sequence of automated steps. Upon completion, it produces a tree-based machine learning classifier in both Extensible Markup Language (XML) and Verilog formats. The XML output represents the classifier's hierarchical structure, while the Verilog code serves as a hardware description language (HDL) model. This Verilog output is then used in a Field Programmable Gate Array (FPGA) design validation flow to confirm the model's performance.Subsequently, the framework seamlessly transitions into an Application Specific Integrated Circuit (ASIC) flow to build a customized classifier chip. The framework's uniqueness lies in bridging the gap between model training and hardware design, offering a streamlined approach for implementing machine learning classifiers as integrated circuits. This paper also addresses several key challenges encountered during the design automation and implementation stages, which are critical in transforming raw data into functional, high-performance classifier chips. The proposed framework, operating at 100 MHz, demonstrates an average 10-fold cross-validation accuracy of 80.79% across five datasets, highlighting its effectiveness in producing low-cost, efficient classifiers suitable for real-time applications.

Introduction

This paper presents a novel framework that automates the design and implementation of machine learning classifier chips directly from raw data. It accepts data in CSV format and performs a sequence of steps, including data processing, feature engineering, and model training, to generate a trained classifier model. This model is then converted into two formats: XML for hierarchical visualization and Verilog for hardware description. The Verilog output enables verification on Field Programmable Gate Arrays (FPGA), allowing rapid validation of classifier performance in a reconfigurable hardware setting[1]. Once validated, the framework proceeds to Application Specific Integrated Circuit (ASIC) synthesis, effectively bridging machine learning model training and its integration into hardware. The framework's design flow supports creating high-performance,low-cost classifier chips suited for real-time applications. Performance was tested across five datasets, achieving an average 10-fold cross-validation accuracy of 80.79% at 100 MHz, demonstrating its utility for applications like image recognition and natural language processing[4]. The paper details both the framework's design process and its unique contributions, including addressing the challenges of data conversion, resource optimization, and real-time performance in hardware environments.
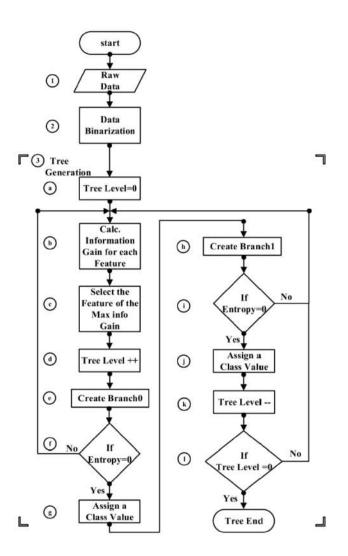
Fig. 1: C program flow chart(Courtesy : ResearchGate)

Design Automation

The first component of the framework focuses on automating the data processing and model training stages, using a systematic approach to prepare datasets and generate a machine learning model suited for hardware implementation[3]. The process begins by taking a dataset in CSV format, which undergoes several key preprocessing steps. Data binarization as shown is applied to convert nominal values into binary format, enabling compatibility with digital circuit design. Feature selection is then performed to identify the most informative features, followed by model training using the ID3 algorithm, a popular decision tree classifier that calculates information gain to make decisions at each tree node. This approach provides a robust structure for classifier logic in hardware. Once the model is trained, the framework generates two output files: an Extensible Markup Language (XML) file and a Verilog file in fig[1]. The XML file serves as a visual representation of the decision tree hierarchy, useful for debugging and data organization, while the Verilog file encodes the decision tree logic in a hardware description language (HDL) in fig[2] format[2], making it suitable for direct input into hardware synthesis tools.

```
<? xml version ="1.0" encoding="UTF-8" ?>
    <root name="overcast">
        <child0 name="highHumidity">
            <child0 name="weakWind">
                <child0 name="sunny">
                    <child0> class1 </child0>
                    <child1> class0 </child1>
                </child0>
                <child1> class0 </child1>
            </child0>
            <child1 name="sunny">
                <child0 name="weakWind">
                    <child0> class1 </child0>
                    <child1> class0 </child1>
                </child0>
                <child1> class1 </child1>
            </child1>
        </child0>
        <child1> class0 </child1>
    </root>
```
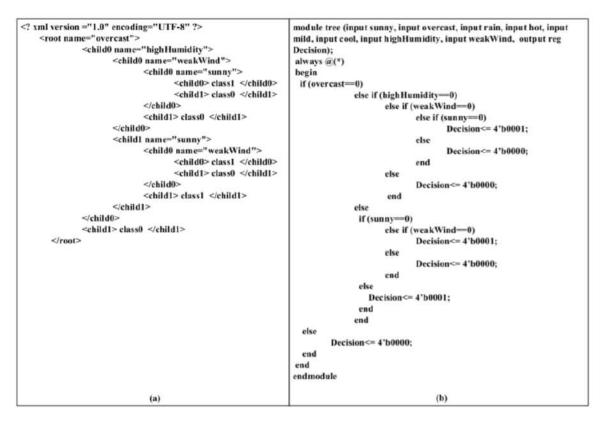
```
module tree (input sunny, input overcast, input rain, input hot, input
mild, input cool, input highHumidity, input weakWind, output reg
Decision);
always @(*)
begin
  if (overcast==0)
                  else if (highHumidity==0)
                          else if (weakWind==0)
                                  else if (sunny==0)
                                          Decision<= 4'b0001;
                                  else
                                          Decision<= 4'b0000;
                                  end
                          else
                                  Decision<= 4'b0000;
                          end
                  else
                  if (sunny==0)
                          else if (weakWind==0)
                                  Decision<= 4'b0001;
                          else
                                  Decision<= 4'b0000;
                          end
                  else
                          Decision<= 4'b0001;
                  end
          end
  else
          Decision<= 4'b0000;
  end
end
endmodule
```

(a)   (b)

Fig. 2: Generated files: (a) XML tree representation, (b) Hardware description representation in Verilog[1]

FPGA and ASIC Implementation

The second part of the framework focuses on verifying and implementing the classifier model as an integrated circuit. This flow begins with design verification using a Field Programmable Gate Array (FPGA)in fig[3], where the generated Verilog code is synthesized, and functional and timing verifications are conducted to ensure accuracy. FPGA prototyping allows the design to be evaluated in a flexible, reconfigurable environment, providing an opportunity to identify any issues before committing to the ASIC flow in fig[4]. Once the design is verified, it proceeds to the ASIC synthesis process. Here, the Verilog code is synthesized into a gate-level netlist, followed by placement, routing, and layout generation. These steps map the design to physical cells and interconnects, defining the chip's structure. The flow ultimately produces a GDS file, the standard format for chip fabrication, which includes detailed instructions for manufacturing the IC.

The novelty of this framework lies in its seamless integration from data to hardware eliminating the need for manual coding or configuration adjustments and thus reducing design time and potential errors[1]. Additionally, by automating feature engineering, model training, and HDL generation, the framework can rapidly produce customized ML classifier ICs that are optimized for speed, accuracy, and power efficiency. This makes the framework particularly valuable for applications requiring real-time data processing, such as live video analysis, sensor data processing, and other high-speed environmentswhere software-based ML solutions may fall short[3].

Overall, this framework represents a significant advancement in the field of electronic design automation for machine learning[1], providing researchers and developers with a powerful tool to quickly and effectively implement ML models as high-performance,low-cost hardware solutions.
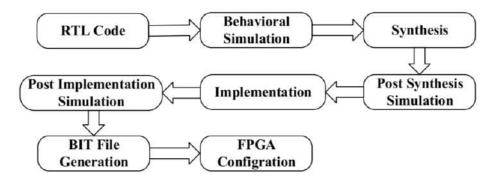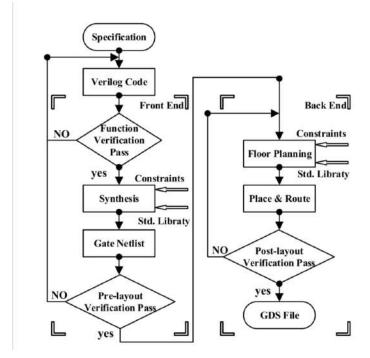
Fig. 3: FPGA design flow[2]

Fig. 4: ASIC design flow(Courtesy : ResearchGate)

Results and Discussion

The Results and Discussion section evaluates the framework's effectiveness in generating machine learning classifier chips using five datasets: Balance-Scale, Bloggers, Car Evaluation, Lenses, and SPECT. Key metrics analyzed include accuracy, latency, throughput, and resource utilization for both FPGA and ASIC implementations. The framework achieves an average 10-fold cross-validation accuracy of 80.79%, demonstrating competitive performance. The FPGA implementation on the UltraScale VCU108 validates functionality, with resource usage varying based on tree depth and binary features[3]. The ASIC design phase** involves synthesis and physical layout, confirming efficient power consumption due to the combinational logic-based design. Power analysis reveals a linear relationship between clock frequency and power consumption, emphasizing the framework's efficiency in real-time environments[4].

Comparisons with existing classifiers (C4.5, ID3, Naïve Bayes) show similar accuracy levels[3], supporting the framework's robustness. Larger datasets, like Balance-Scale, demand higher resources, impacting area and power requirements. The study underscores the scalability and adaptability of the framework for efficient classifier chip design, with potential for further optimization in resource-constrained applications.
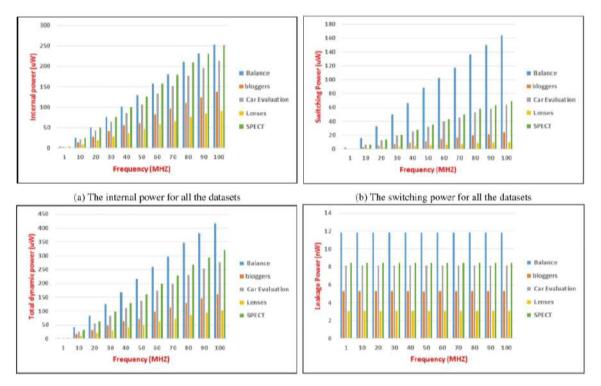
Fig. 5: The impact of changing the frequency on the power consumption(Courtesy : ResearchGate)

Future Work

Future work will focus on extending the framework's capabilities and addressing current limitations. The first priority is to refine the data binarization process, which is currently limited to nominal data. By incorporating support for numeric features, the framework could adapt to a broader range of datasets and classification tasks, potentially improving the accuracy and flexibility of the generated models. Another area of exploration involves the entropy-based decision criteria used in the ID3 algorithm. Currently,the framework relies on a strict entropy-based condition to split data, which can lead to overfitting in some cases. Relaxing this entropy condition may allow for more generalized models, reducing over fitting and enhancing classifier robustness, especially when handling larger datasets with higher feature variability. Designing and implementing machine learning classifier chips pose several challenges due to the complex requirements of hardware-based AI models. Key obstacles include balancing high performance with energy efficiency, managing limited memory and data transfer bottlenecks, and achieving scalability across diverse models. Issues such as quantization accuracy in Figure 3.1 , thermal management, and testing reliability also complicate the process. Additionally, limitations in current design automation tools add to the difficulty, making it essential to innovate at both the architectural and tooling levels to support efficient, adaptable ML hardware solutions.

Conclusion

This work presents a fully automated framework that directly converts raw datasets into integrated circuits (ICs) for machine learning, bridging a gap in ASIC design automation. By transforming data into Verilog-based hardware descriptions, it enables rapid prototyping for real-time applications like image recognition and NLP. Unlike traditional methods, the process is fully autonomous, covering data preprocessing, model training, and Verilog generation.

Validated across five case studies, the framework achieved 97.28% testing accuracy, 80.79% cross-

PERIPHERAL DIMMING:A NEW LOW-POWER TECHNOLOGY FOR OLED DISPLAY BASED ON GAZE TRACKING

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Abstract

The technology presents a new low-power technology for OLED displays, termed peripheral dimming, which leverages gaze tracking. The method seeks to conserve power without compromising perceptual image quality by progressively dimming the peripheral areas of the screen according to their distance from the gaze point. Quantitative conditions for maintaining image quality were examined through a psychophysical experiment using three video clips. A lightness reduction ratio (LRR), representing the luminance reduction per viewing angle based on lightness, was proposed. Four LRR conditions ranging from 0.1 to 1.0% degree were applied to each clip. The experiment employed a two-alternative forced choice design, where participants compared test clips using the proposed method to the original clips and identified the brighter one presented in random order. The LRR threshold at which differences became noticeable was determined. Results show the proposed method can reduce OLED display power consumption by up to 34.4% while maintaining high image quality, with a mean structural similarity index above 0.94. This approach supports low-power operation of OLED displays in head-mounted devices while ensuring a high-quality viewing experience.

Introduction

OLED displays, known for their self-luminous properties, outperform LCDs in terms of viewing angles, color gamut, response speed, and thinness[2]. These advantages have driven their rapid adoption in mobile devices like smartphones and head-mounted displays (HMDs). Despite advancements aimed at achieving higher resolution and luminance, the luminance in OLEDs directly correlates with electric current, making power consumption a critical issue. Various hardware- and software-based techniques have been proposed to address this challenge, such as dynamic voltage scaling, adaptive display modes, and pixel data modification. However, these hardware-based solutions often require specialized components, limiting their practicality in real devices.

Software-based solutions, including brightness scaling (BS) and contrast enhancement (CE), have been explored to balance power savings and image quality. BS adjusts the brightness by remapping the gray-level curve, while CE techniques, like power-constrained contrast enhancement (PCCE) and low-overhead adaptive power saving and contrast enhancement (LAPSE), enhance image contrast and save power[3]. While these methods leverage objective image quality assessments (IQA) to optimize efficiency, they face challenges as IQA may not always align with actual perceived image quality, leading to noticeable differences for users.

Human visual system (HVS)-based approaches have also been investigated to address the perceived quality issue. Studies have explored reducing brightness via alpha blending, turning off selective subpixels, or dimming areas of lesser attention, such as screen edges in FPS games or areas covered by a user's fingers[1]. While effective in some scenarios, these methods often fail when the user's actual focus of attention deviates from the predicted areas, limiting their general applicability.

To overcome these limitations, this proposesd a novel low-power technology for OLED displays called peripheral dimming, which leverages gaze tracking. Insp $\sqrt{}$ 1 by foveated rendering technology, this method reduces luminance in peripheral vision areas based on the user's gaze point, aligning dimming regions with actual user focus[4]. The proposed approach introduces a human visual system-based metric, the lightness reduction ratio (LRR), to determine the optimal luminance reduction. Psychophysical experiments and statistical analysis were conducted to identify the LRR threshold that minimizes power consumption without degrading perceived image quality.

The rest of this method is organized as follows: Section II reviews the theoretical background. Section III details the proposed method and its objectives. Section IV describes the psychophysical experiment design, and Section V presents the experimental results, validating the effectiveness of the proposed peripheral dimming technology.

Power Model of OLED Display

- Power consumption in OLED displays is proportional to luminance, where a pixel's power usage depends on its linear RGB values, which have a linear relationship with gamma-expanded luminance values[3].
- A pixel's total power consumption is modeled as $P_{display} = f(R) + f(G) + f(B) + C$, where $f(R)$, $f(G)$, and $f(B)$ represent the power consumed by the red, green, and blue subpixels, respectively, and C accounts for static power consumed by non-pixel components.
- Each subpixel's power consumption follows the formula $f(X) = \omega_X X^\gamma$, where X is the digital RGB value, ω_X is the weighting factor (determined by the OLED panel's physical properties), and γ, the gamma value, is typically figure 1. This study uses the coefficients $(\omega_R : \omega_G : \omega_B) = (70 : 115 : 154)$ as adopted from previous research.
- Ignoring static power C, the total dissipated power (TDP) for displaying a color image is calculated as $TDP = \sum_{i=1}^{N} \sum_{j=1}^{M} [f(R_{i,j}) + f(G_{i,j}) + f(B_{i,j})]$, where i and j are the horizontal and vertical pixel indices, and N and M are the total horizontal and vertical pixel counts, respectively.

Human Visual System

- The retina has two types of photoreceptor cells: cone cells, responsible for color vision in bright light, and rod cells, which are more sensitive to low light[3]. Cone cells are densely packed in the fovea and decrease rapidly in the periphery, while rod cells are concentrated in the periphery and gradually decrease from their peak distribution.
- Under bright conditions, human vision relies on photopic vision dominated by cone cells. Due to the limited presence of cone cells in the peripheral retina, peripheral vision is less sensitive to changes in brightness.
- Human vision exhibits a nonlinear relationship between perceived brightness and luminance[2]. For example, the eye is highly sensitive to luminance changes in darker regions but less sensitive to similar changes in brighter areas.
- The CIELAB color space accounts for human visual sensitivity, with its lightness component (L^*)

reflecting perceived brightness. The L^* value is calculated as a power function of luminance:

$$L^* = 116f\left(\frac{Y}{Y_w}\right) - 16, \quad f(t) = \begin{cases} t^{1/3}, & \text{if } t > \left(\frac{6}{29}\right)^3 \\ \frac{1}{3}\left(\frac{29}{6}\right)^2 t + \frac{4}{29}, & \text{otherwise} \end{cases}$$

Here, Y and Y_w represent the luminance of a pixel and a white pixel, respectively, with L^* ranging from 0 (black) to 100 (white).
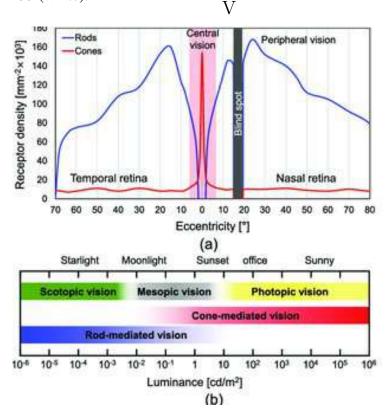
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Fig. 1: (a) Distribution of rods and cones depending on the eccentricity from the fovea of the human eye and (b) approximate ranges of the photoreceptor regimes (Courtesy : ReasearchGate)

Psychophysical Analysis

- The study is grounded in psychophysics, focusing on the relationship between stimuli and sensations. It utilizes the two-alternative forced choice (2-AFC) method, where subjects must select between two options, and the correct response rate is recorded. The threshold level, representing the stimulus intensity at which a difference is detectable, is set at a 75% correct response rate[4].
- The psychometric function, represented as an S-shaped sigmoid curve shown in figure 2, is a statistical model that estimates the relationship between the probability of correct responses and stimulus intensity[2]. It includes parameters for lapse rate , guess rate (Y), stimulus level (x), threshold level (m), and width (w), with the cumulative Gaussian function used to model the curve.
- The study applied the psignifit 4 package for MATLAB, an open-source tool that uses Bayesian inference to fit a beta-binomial model to experimental data. The package estimates the psychometric function by analyzing correct response rates at different stimulus levels.
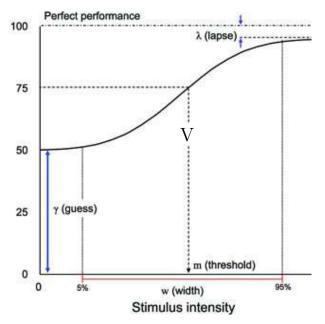
Fig. 2: Example of the psychometric function and parameters (Courtesy : ResearchGate)

Peripheral Dimming

The peripheral dimming method utilizes gaze tracking to save display power by darkening peripheral pixels without degrading image quality. Input images are converted into the CIELAB color space, isolating lightness (L*) and color components (a*, b*). A lightness reduction ratio (LRR) matrix is calculated based on the gaze position and applied to adjust peripheral brightness. Within a central gaze zone (10° viewing angle), pixels retain their original brightness[3]. Beyond this zone, lightness decreases linearly as shown in figure 3

- Peripheral dimming aims to reduce power consumption in eye-tracker-integrated HMDs like VR/AR headsets by lowering peripheral brightness without compromising image quality. Building on prior methods like dimming boxes[1], this study identifies threshold lightness reduction ratio (LRR) levels for maintaining image quality and explores a gaze-adaptive approach. Initially, the focus is on fixed central gaze points to evaluate its impact across different images.
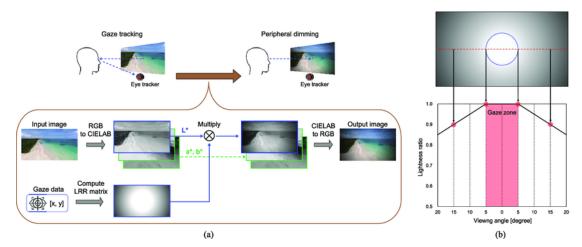

Fig. 3: (a) Framework of the proposed method and (b) lightness ratio depending on the viewing angle in the case of gazing at the center of the screen(Courtesy : ResearchGate)

Psychophysical Experiment

Design

The experiment employed two methods: double stimulus (DS) and two-alternative forced choice (2-AFC). The DS method, based on ITU-R BT.500-11, displayed a fixation image with a red crosshair for three seconds, followed by reference and test videos shown in figure 4 sequentially for eight seconds in random order[2]. Subjects voted for the brighter video after a three-second gray screen and had ten seconds to respond. The 2-AFC method required subjects to choose the brighter video between two options.
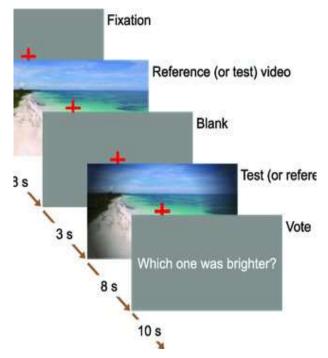

Fig. 4: Schematic diagram of an assessment unit[2]

Condition

Three video clips in figure 5 (1920 × 1080 resolution) were used, with frames modified to include a red crosshair as the gaze point. A virtual 8° allowed zone ensured valid responses[3], triggering a beep alert if subjects looked outside it. Four LRR conditions (0.1, 0.4, 0.7, and 1.0%/degree) were applied, and lightness adjustments were made in the CIELAB color space before reverting to RGB for video creation.

Procedure

The experiment was conducted in a dark room to eliminate ambient light interference and ensure consistent viewing conditions. A 24-inch LCD monitor was used to display the video content, and a Tobii eye tracker was employed to monitor participants' gaze positions accurately. The dark room setting helped isolate the effects of luminance reduction, ensuring that external lighting did not influence participants' visual perception. The Tobii eye tracker was calibrated individually for each participant to ensure precise gaze-tracking accuracy. This setup allowed the researchers to accurately measure how changes in luminance reduction ratio (LRR) affected perception and power savings under controlled conditions.
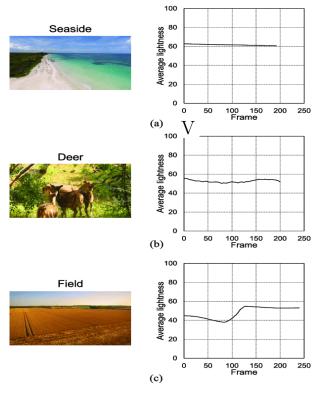
Fig. 5: Frame image and average lightness of all frame images of (a) Seaside, (b) Deer, and (c) Field clips(Courtesy : ResearchGate)

Result

The study analyzed the impact of the luminance reduction ratio (LRR) on human perception and power savings in OLED displays using gaze tracking technology. OLED displays offer exceptional image quality but consume significant power due to the brightness of individual pixels. The study explored how reducing brightness based on gaze position could optimize power consumption without compromising perceived image quality. By adjusting luminance according to the user's gaze direction, the researchers tested different LRR values and measured both perceptual quality and power savings. Results showed that at an LRR of 0.1% per degree, the differences from original clips were nearly imperceptible, but correct answer rates increased as LRR rose. A key finding was the identification of a threshold LRR (LRRTH) at which the correct answer rate reached 75%, varying across video clips depending on their average lightness. Statistical analysis revealed that LRRTH was inversely related to average lightness — brighter clips tolerated lower LRR values, while darker clips allowed more aggressive luminance reduction. Applying LRRTH resulted in power savings of 11.0%, 21.0%, and 34.4% for high, medium, and low-brightness clips, respectively, surpassing traditional brightness reduction methods while maintaining higher perceived image quality.

Objective assessments, including the structural similarity index (SSIM), confirmed negligible image degradation even at reduced luminance levels. The study demonstrated that gaze-tracking-based luminance adjustment ensures stable perceived image quality even during gaze shifts, providing a smooth and consistent viewing experience. This approach allows for significant power savings without noticeable loss in visual quality, making it a promising low-power technology for OLED displays. The discovery of LRRTH linked to average lightness suggests a foundation for a predictive model that could further enhance power efficiency. This method could be integrated into next-generation OLED panels, smart TVs, smartphones, and VR/AR devices, where balancing power efficiency and display quality is critical.

Future research may explore adaptive LRR models that adjust in real-time based on content type and user behavior, paving the way for more intelligent, energy-efficient display technologies.
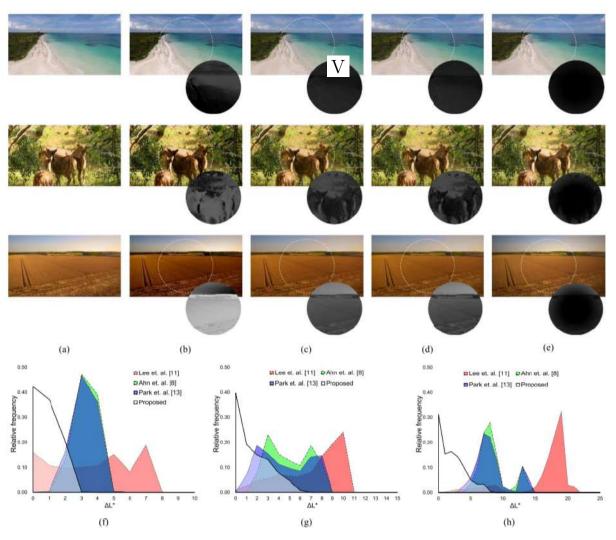

Fig. 6: Visual comparison between (a) the original images and the modified images generated by (b) [11], (c) [8], (d) [13], and (e) the proposed method. The circular images illustrate within the area between the original and modified images. Distribution graphs of (f) Seaside, (g) Deer, and (h) Field images.[3]

Conclusion

This paper proposes peripheral dimming, a low-power technology for OLED displays that reduces luminance in peripheral vision areas. A psychophysical experiment determined that the LRR threshold (LRRTH) is inversely proportional to average lightness, with potential for a quantitative model in future studies. The method achieves up to 34.4% power savings while maintaining perceptual and objective image quality. Designed for self-luminous displays like OLED and micro-LED, it is particularly suitable for HMDs, especially as integrated eye-tracking becomes more common. This makes peripheral dimming a promising energy-efficient solution for VR and AR devices.

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AI-BASED SATELLITE GROUND COMMUNICATION SYSTEM WITH INTELLIGENT ANTENNA POINTING

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Abstract

The "AI-based Satellite Ground Communication System with Intelligent Antenna Pointing" project introduces an innovative approach to satellite communication by leveraging artificial intelligence to optimize antenna positioning. Traditional systems struggle to maintain signal quality in dynamic environments, leading to inefficiencies. This project incorporates advanced AI algorithms, such as FI-GRU and II-DRL, to automate and enhance antenna alignment processes. These algorithms predict optimal antenna angles and dynamically adjust parameters like azimuth, elevation, and polarization to maximize signal strength while minimizing interference. By significantly reducing alignment time and improving accuracy, this technology promises to revolutionize satellite communication, enabling seamless connectivity in challenging terrains and boosting applications in defense, remote connectivity, and disaster management.

Introduction

In the modern era of globalized information exchange, communication systems play a critical role in ensuring seamless connectivity across diverse and remote regions[6]. Satellite communication systems have become indispensable, particularly in areas where traditional communication infrastructures face deployment challenges, such as deserts, forests, or mountainous terrains. These systems not only facilitate social interactions, but also serve crucial functions in national defense and industrial operations.

A core component of satellite communication systems is the Satellite Earth Station (SES), which acts as a relay point for transmitting and receiving data between satellites and ground users. Accurate alignment and real-time tracking of satellite antennas are essential to ensure optimal signal reception and uninterrupted communication. However, dynamic environmental conditions, satellite movements, and system complexities pose significant challenges to traditional antenna-pointing mechanisms.

This seminar report explores the integration of Artificial Intelligence (AI) technologies in satellite ground communication systems to address these challenges. The implementation of AI-based algorithms[2], such as the Fast Iterative Gated Recurrent Unit (FI-GRU) and Intelligent Improved Deep Reinforcement Learning (II-DRL), offers a transformative approach to optimizing antenna pointing and tracking. These algorithms improve efficiency by adapting to dynamic environments, reducing adjustment times, and improving signal reception quality.

The report provides a detailed analysis of the architecture, functionality, and benefits of AI-driven satellite communication systems, emphasizing how artificial intelligence enhances the efficiency and
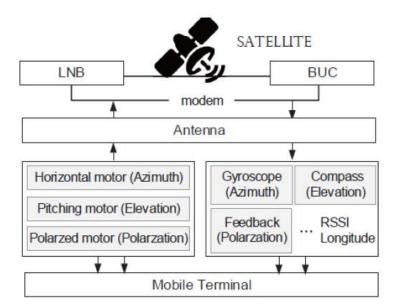
Fig. 1: The AI-based multi-layer network framework of the satellite-terrestrial communications[4]

Fig. 2: A-A Algorithm[5]

reliability of satellite networks. The proposed system leverages advanced AI algorithms to optimize various aspects of satellite communication, including signal processing, resource allocation, interference management, and network adaptability. The architecture is designed to handle complex satellite communication scenarios by using machine learning and deep learning models to predict and respond to changing network conditions in real-time. The system's functionality includes dynamic beamforming, automated error correction, and intelligent bandwidth allocation, ensuring that communication remains stable and efficient even under high traffic loads or adverse environmental conditions. By integrating AI into the core of satellite communication, the system can anticipate disruptions and automatically adjust parameters to maintain optimal performance[8].

Algorithm 2 Fast Iterative GRU Algorithm ((FI-GRU))

Require: $pelegra_0, \mathcal{N}$

1: Initialize counters: $N = 0, pelegra_0 = 0$.
2: **if** $relegra_i > Q$ **then**
3:     The satellite signal value is predicted state $i + 1 : f(elepar_i, elegra_i, \rho) = amp_{i+1}$.
4:     Calculate the gradient $pelegra_{i+1} = \frac{amp_{i+1} - amp_i}{elepar_{i+1} - elepar_i}$
5:     Update $N = N + 1$, $elepar_i = elepar_{i+1}, pelegra_i = pelegra_{i+1}$.
6: **else**
7:     The elevation of the antenna output GT has an optimal adjustment angle of $elepar_N$.
8: **end if**

Fig. 3: FI-GRU Algorithm[3]

Algorithm 3 Intelligent Improved DRL Algorithm (II-DRL)

Require: $T, \mathcal{N}$

1: Initialize counters: $eler_0 = 0, E_{value} = 0$.
2: **for** $t = 1, \cdots, T$ **do**
3:     Observe E_{value} and $eler_t^i$ at time spot t,

$$E_{value} = E_{value} + \frac{1}{t} \frac{amp_t - amp_{t-1}}{value_t - value_{t-1}} \quad (4)$$

4:     $D_{atc_t} = E_{value} * value_t$
5:     **if** $D_{atc_t} \le 0$ **then**
6:         $eler_t^i = \theta \div t$
7:     **else**
8:         $eler_t^i = t * (amp_t^i - amp_{t-1}^i)$
9:     **end if**
10:     Select the action with maximum reward function to move: $Q(s_t, a_t) = E(r_{t+1} + \gamma \min_{a'} Q(s_{t+1}, a'))$
11: **end for**

Fig. 4: II-DRL Algorithm[6]

Design and Experimentation

The design and experimentation of the "AI-based Satellite Ground Communication System with Intelligent Antenna Pointing" focus on leveraging artificial intelligence to address critical challenges in modern satellite communication systems[5]. The design is centered around optimizing antenna alignment, tracking, and signal strength reception, especially in dynamic and complex environments. By employing advanced algorithms like the Auto-Acquire (AA), Fast Iterative Gated Recurrent Unit (FI-GRU), and Intelligent Improved Deep Reinforcement Learning (II-DRL), the system automates key processes to enhance efficiency and minimize human intervention.

The core design involves a multi-layered network framework that integrates satellites, ground stations, and user terminals. The satellite earth station (SES) uses AI algorithms to collect data from gyroscopes, compasses, and signal detectors, enabling real-time adjustments in azimuth, elevation, and polarization.

This ensures continuous optimal signal reception, even as satellites and environmental conditions change. The incorporation of FI-GRU predicts optimal antenna angles based on historical data, while II-DRL dynamically adapts to environmental shifts, ensuring robust performance in various scenarios.

Experimentation involved building a simulation platform to test the performance of these algorithms[10]. The study demonstrated that both FI-GRU and II-DRL significantly reduce the time required for satellite pairing tasks compared to traditional AA algorithms. The results revealed enhanced tracking precision, reduced adjustment time, and improved communication reliability. This validated the potential of AI-driven systems to revolutionize satellite communication by automating complex tasks and ensuring efficient resource utilization.

Overall, the project sets the stage for future advancements in satellite-ground communication, highlighting the role of AI in achieving real-time adaptability, scalability for global networks, and enhanced communication in remote areas.

Result and Discussion

The research presents an innovative approach to enhancing satellite ground communication systems through AI-driven antenna pointing algorithms. The experimental results demonstrated significant advancements in satellite tracking and communication efficiency. Utilizing AI techniques such as the Fast Iterative Gated Recurrent Unit (FI-GRU) and Intelligent Improved Deep Reinforcement Learning (II-DRL) algorithms, the project successfully optimized antenna alignment, reducing the time required for satellite pairing and improving signal strength under dynamic conditions.

The FI-GRU algorithm's ability to analyze historical data and predict optimal antenna parameters allowed for faster response times[9]. It efficiently handled the challenges posed by satellite movement and environmental variability, outperforming traditional Auto-Acquire (AA) algorithms in azimuth, elevation, and polarization adjustments. This efficiency was evident in experiments where the FI-GRU algorithm consistently demonstrated reduced adjustment times for antenna parameters compared to conventional methods.

Meanwhile, the II-DRL algorithm excelled in adapting to real-time changes in the satellite environment. By leveraging reinforcement learning principles, it dynamically adjusted antenna parameters to ensure consistent signal reception. The II-DRL algorithm's adaptability proved critical in scenarios involving multiple satellite pairing requests, as it balanced exploration and exploitation to achieve optimal antenna positioning. This approach significantly minimized the time required for antenna fine-tuning while enhancing the overall system robustness.

A key finding was the superior performance of AI-based algorithms in maintaining optimal communication in complex environments[7]. The project highlighted the limitations of traditional methods, which often failed to account for dynamic conditions and required extensive manual intervention. In contrast, AI-based systems offered a scalable, autonomous solution capable of managing high-volume satellite communication tasks efficiently.

In conclusion, the integration of AI technologies into satellite communication systems marks a pivotal step toward achieving real-time adaptability, reduced latency, and improved service quality. This research not only sets a benchmark for future developments in satellite ground communication but also underscores the transformative potential of artificial intelligence in overcoming the challenges of modern communication demands.
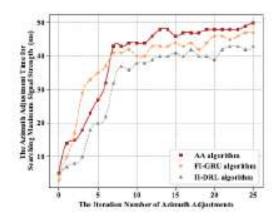
Fig. 5: Impact of Azimuth Adjustment Iterations on Ta that was achieved by AA, the proposed FI-GRU and II-DRL[4]
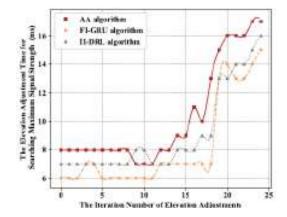

Fig. 6: Impact of Elevation Adjustment Iterations on SAA task that was achieved by AA, the proposed FI-GRU and II-DRL[4]
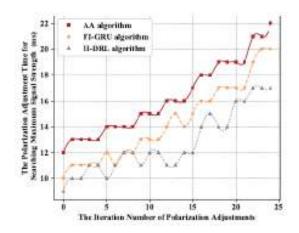

Fig. 7: Impact of Polarization Adjustment Iterations on SAA Task that was achieved by AA, the proposed FI-GRU and II-DRL[4]

Conclusion

The "AI-Based Satellite Ground Communication System with Intelligent Antenna Pointing" introduces cutting-edge AI technologies like reinforcement learning and neural networks to revolutionize satellite communication. By optimizing antenna alignment in real-time, it reduces signal search times, enhances communication efficiency, and ensures robust performance even in dynamic environments. This innovation paves the way for faster, more reliable satellite connectivity, transforming global communication systems.

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WILLOW: STATE OF THE ART

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Abstract

Willow, Google's cutting-edge quantum chip, is designed to push the boundaries of computation beyond classical limits. With the power of superposition and entanglement, Willow performs mathematical calculations in minutes that traditional supercomputers would take hundreds of years to complete[3]. This paper explores the advancements of Willow, highlighting its impact on quantum computing, error correction, scalability, and real-world applications. Despite challenges like decoherence and high cost, Willow stands as a revolutionary leap toward practical quantum computing.

Introduction: The Rise of Quantum Computing

Imagine a world where computers no longer struggle with complex calculations but solve them in the blink of an eye. Meet Willow, Google's cutting-edge quantum chip, designed to push the boundaries of computation beyond classical limits. With the power of superposition and entanglement, Willow isn't just another processor—it's a glimpse into the future of technology, where problems once deemed impossible become solvable. Sleek, sophisticated, and revolutionary, Willow is not just a chip; it's a quantum leap into tomorrow[1]. Willow needs less than five minutes to perform a mathematical calculation that one of the world's most powerful supercomputers could not complete in 10 septillion years, a length of time that exceeds the age of the known universe.

Fig. 1: Google's Quantum Computing System [1]

How Willow Stands Out from the Rest

While most quantum chips struggle with stability and error correction, Willow takes a bold step forward. Engineered by Google's top minds, it boasts more reliable qubits, improved error resilience, and an architecture designed for scalability. Unlike its predecessors, Willow isn't just an experiment—it's a serious contender in the race for quantum supremacy[2]. In a world where every qubit counts, Willow is built to go further, compute faster, and unlock possibilities beyond imagination.

- **Better Qubit Stability** – Willow has improved coherence time, meaning qubits stay stable longer for calculations
- **Enhanced Error Correction** –Uses advanced techniques to reduce quantum errors, making computations more reliable.
- **Scalability** – Designed to handle more qubits efficiently, moving closer to practical quantum computing.
- **Speed and Performance** – Processes complex problems exponentially faster than classical supercomputers.
- **Optimized for Real-World Applications** – Unlike older chips, Willow is a step toward solving real scientific and industrial problems.
- **Google's Quantum Breakthroughs** – Builds on Google's quantum supremacy claim, refining its technology for better results.
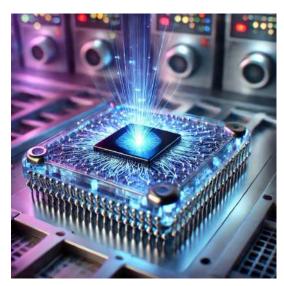
Fig. 2: Quantum Chip [2]
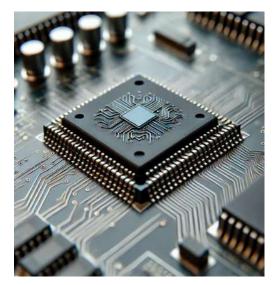
Fig. 3: Regular Chip [2]

Advantages of Willow Quantum Chip

- **Higher Computational Power** – Leverages quantum superposition and entanglement for solving complex problems faster than classical chips.
- **Enhanced Security** – Uses quantum encryption, making communication nearly impossible to hack.
- **Energy Efficiency** – Consumes significantly less power compared to traditional processors.
- **Scalability** – Designed with improved qubit stability, allowing better scaling for future quantum computing applications.
- **Improved Error Correction** – Integrates advanced error-correction techniques to enhance computational accuracy

Challenges/Limitations of Willow Quantum Chip

Despite its advantages, the Willow Quantum Chip faces several challenges that hinder its widespread adoption and performance optimization[3]. These include technical, economic, and practical limitations that researchers are actively working to overcome. Some of the key challenges are:

- **Quantum Decoherence** – Qubits are highly sensitive to environmental noise, leading to errors in computation.
- **High Cost** – Quantum chips require advanced fabrication techniques, making them expensive to develop and maintain.
- **Error Correction Complexity**- Despite improvements, quantum error correction remains a major challenge in maintaining stable computations.

Applications of Willow Quantum Chip

The Willow Quantum Chip is set to revolutionize multiple industries with its groundbreaking capabilities. In computing, it accelerates processing speeds, allowing for more efficient and powerful calculations. In artificial intelligence, it enhances machine learning, enabling faster and more accurate predictions.

In cryptography, the chip could lead to the development of ultra-secure encryption methods, safeguarding data against quantum decryption[2]. The healthcare sector stands to benefit as well, with the chip's ability to simulate molecular structures speeding up drug discovery and potentially saving lives.

Additionally, the chip's efficiency promises to optimize energy use across industries and improve quantum communication systems, making data transmission more secure. The Willow quantum chip is paving the way for a future where technological limitations are constantly redefined.

Conclusion: The Dawn of a Quantum Future

The Willow Quantum Chip marks the dawn of a new era in technological innovation. With its unparalleled potential across computing, artificial intelligence, cryptography, healthcare, and energy, this quantum breakthrough is not just a glimpse into the future but a glimpse of the future itself. As industries embrace this transformative technology, we stand on the brink of unprecedented advancements—ushering in a world where quantum solutions solve some of humanity's most complex challenges. The Willow chip is more than just a tool; it is a catalyst for the future, shaping the landscape of tomorrow's technologies and sparking the limitless possibilities that quantum computing offers.

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BASIC ELECTRONICS

ULTRASONIC ACOUSTIC LEVITATION

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Abstract

An acoustic levitator can suspend small, lightweight particles, such as a styrofoam ball, in mid-air. In this study, a sound field is generated by configuring ultrasonic sensors with the help of an Arduino Microcontroller. A standing wave is generated as a result of the collision of the sound waves, which consists of nodes (points of no displacement) and antinodes (points of maximum displacement), it creates a region where objects can be suspended due to acoustic pressure differences. Placing the object at these pressure points enables levitation. The experimental setup, which includes an H-Bridge and a 12V power supply, successfully levitated small particles within the acoustic field. Precise frequency calibration and sensor alignment are of utmost importance for levitation. Acoustic levitation has various potential applications in scientific fields, including contactless material handling, studying the properties of fluids and particles in outer space, and aesthetic purposes.

Introduction

Acoustic levitation is a fascinating technology that integrates physics, engineering, and technology. The technology employs high-frequency sound waves to create a field capable of counteracting gravity. Standing waves, formed through the superposition of sound waves, generate pressure points, enabling objects to float . A standing wave is a wavefront that does not change with time. At the nodes, the pressure level is at a minimum such that the pressure is greater above and below the point due to the placement of the anti-nodes and around the point where the pressure is equal to atmospheric pressure. Therefore, a particle placed at this point would feel a constant pressure in the radial direction point inwards. For levitation to occur, the acoustic pressure must match the weight of the object. This technology enables contactless manipulation of materials, which makes it a versatile and innovative tool for various applications and advancements. In the acoustic field, during the phase of rarefaction of an acoustic wave, the molecules of air are compressed and generate a pressure higher than atmospheric. In the case of the built levitator, the pressure will depend on the intensity applied to the transducers. The acoustic pressure generated by the levitator is high enough to extinguish small fires. In 3D printing, levitation technology enables the creation of structures layer by layer without the need for any supporting material, which enhances its precision and accuracy. In the pharmaceutical industry, it can be used for drug development, wherein precise manipulation of small droplets and the development of accurate dosages can be achieved. In the case of material processing, the delicate and reactive matter can be processed without any contamination or damage. In the medical industry, it enables precise and contamination-free diagnostic procedures and tissue engineering. Other applications include environmental studies, research and development of fundamental physics and acoustics, etc. The demonstration setup includes hardware and software components. Hardware components such as an Arduino Uno board, an H-bridge motor driver, a pair of ultrasonic sensors, a 12V (1300 mA) rechargeable battery, and software components such as an Arduino IDE is used. An electrical

signal is generated, which is amplified with the help of H-bridge. The amplified signal is further split into two signals and transmitted to the two sensors equally. The sensors convert the electrical signal into a sound signal that is mechanical in nature. When the mechanical vibrations coincide with each other, they form a standing wave. Hence, particles stay trapped in their nodes and antinodes, thereby showcasing levitation.

Principle of Ultrasonic Acoustic Levitation

The concept of standing waves is fundamental to acoustic levitation. These waves are formed when two sound waves of the same frequency travel in opposite directions and interfere with each other. This interference creates points of minimum pressure (nodes) and maximum pressure (antinodes). Objects placed at these nodes experience an upward force that counteracts gravity, resulting in levitation. For levitation to occur, the acoustic pressure must match the weight of the object. The effectiveness of levitation depends on frequency calibration, sensor alignment, and transducer intensity.
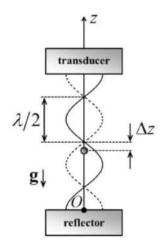

Fig. 1: Standing Wave [1]

Experimental Setup of Ultrasonic Acoustic Levitation

The acoustic levitation system is designed using both hardware and software components that work together to create and control standing sound waves for levitation. The hardware consists of an Arduino Uno, which generates the required frequency for ultrasonic waves, an H-Bridge Motor Driver that amplifies the electrical signals before sending them to the ultrasonic transducers, ultrasonic sensors that emit high-frequency sound waves to create the standing wave pattern needed for levitation, and a 12V rechargeable battery, which supplies power to the entire setup. On the software side, the Arduino IDE is used to write and upload a program to the Arduino Uno, ensuring it generates the correct frequency signals. The working mechanism starts with the Arduino producing an electrical signal, which is strengthened by the H-Bridge motor driver before being sent to the ultrasonic sensors. These sensors then convert the electrical signals into high-frequency sound waves. When these waves meet, they interfere with each other and form a standing wave pattern, creating regions of high and low pressure. Small objects placed at specific points, known as pressure nodes, experience an upward force that counteracts gravity, allowing them to float in mid-air.
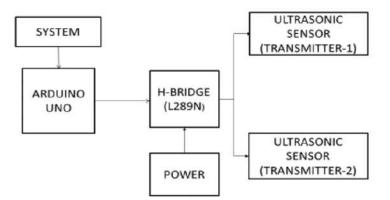
Fig. 2: Block Diagram of Ultrasonic Acoustic Levitation [3]

Working Mechanism of Ultrasonic Acoustic Levitation System

- Signal Generation and Amplification: An Arduino microcontroller generates an electrical signal with a specific frequency, typically in the ultrasonic range (above 20 kHz). This signal is amplified using an H-bridge circuit, which enhances the voltage and current to drive the ultrasonic transducers effectively.
- Ultrasonic Wave Transmission: The amplified signal is fed to ultrasonic transducers, which convert the electrical signal into high-frequency sound waves (ultrasonic waves). These transducers are arranged in such a way that they emit waves in opposite directions, allowing them to interact and interfere constructively.
- Formation of Standing Waves: When two ultrasonic waves of the same frequency travel in opposite directions, they interfere with each other, forming a standing wave pattern. This pattern consists of alternating nodes (points of minimum pressure) and antinodes (points of maximum pressure). The interference creates acoustic radiation pressure, which can exert force on small objects.
- Levitation of Objects: When a lightweight object (e.g., a small bead or droplet) is placed at a pressure node, it experiences an upward force due to the pressure difference. This force counteracts gravity, causing the object to levitate and remain suspended in the air. The stability of levitation depends on the precise control of wave frequencies and the positioning of transducers.

Results and Observations

The system successfully levitates small objects such as styrofoam balls at the pressure nodes of standing waves. The system is designed to levitate lightweight objects such as styrofoam balls, water droplets, or small paper particles at specific locations called pressure nodes within the standing wave field. Ultrasonic transducers generate high-frequency sound waves that interfere to form standing waves, consisting of alternating high-pressure (antinodes) and low-pressure (nodes) regions. Objects placed at these pressure nodes remain suspended in mid-air due to the balance between the gravitational force pulling them downward and the acoustic radiation pressure pushing them upward. By carefully tuning the wave frequency, phase, and amplitude, the position of these nodes can be controlled, enabling precise manipulation of levitated objects. This contactless levitation method has significant applications in biomedical research, microfluidics, space research, and electronics assembly, where contamination-free handling of delicate materials is crucial. Through this mechanism, the system effectively demonstrates how high-frequency sound waves can counteract gravity and enable practical, contact-free object manipulation.
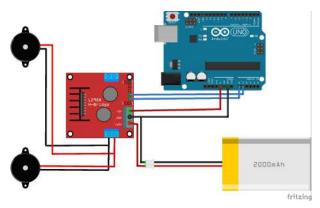
Fig. 3: Levitation of a styrofoam [3]

Fig. 4: Schematic setup of the circuit [2]

Future Prospects

- Non-Contact Manufacturing for Semiconductor Industries: In semiconductor manufacturing, handling delicate materials like silicon wafers is crucial[4]. Traditional methods use mechanical arms or tweezers to move these materials, but this can cause damage or introduce contamination. Acoustic levitation uses sound waves to suspend objects in the air, meaning that materials can be moved without touching them. This eliminates risks like surface scratches or contamination from handling equipment. It's especially important in environments where even the tiniest impurity or defect can cause failures in semiconductor devices, which require extremely precise fabrication processes.
- Medical Applications for Precise Drug Delivery: Acoustic levitation can significantly improve drug delivery systems, particularly in the case of inhalation therapies. In this application, sound waves are used to levitate and precisely direct drug particles, ensuring that the medication reaches specific areas in the body with high precision. For example, in treating lung diseases, levitating the medication can help it target certain areas in the lungs, improving the effectiveness of the treatment and reducing side effects. It's more controlled than traditional delivery methods, allowing for a more personalized approach to medicine.
- Space Exploration for Zero-Gravity Material Manipulation: In space, where there is zero gravity, traditional methods of handling materials (like gravity or mechanical manipulation) are ineffective or impractical. Acoustic levitation provides a way to manipulate materials in this environment. Sound waves can be used to lift and move substances like liquids, powders, and even small objects without the need for physical contact. This could be critical for processes like material synthesis in space, creating fuel from raw materials, or assembling complex structures in space stations or spacecraft.

Conclusion

Acoustic levitation using ultrasonic sensors and Arduino offers a groundbreaking and cost-effective approach to non-contact object manipulation. This innovative technology leverages the power of sound waves to suspend and move objects without physical interaction, providing significant advantages across multiple domains. In science, it enables detailed studies of materials and particles in controlled environments, while in medicine, it promises safer and more precise methods for handling delicate biological samples. The engineering sector also benefits from its potential to manipulate small, fragile components with high precision. As technology continues to evolve, the integration of more advanced sensors, improved control systems, and enhanced acoustic fields will drive the capabilities of acoustic levitation to new heights. The affordability and versatility of Arduino-based systems ensure that this technology will remain accessible to researchers, engineers, and industries, fostering future breakthroughs and innovations. Overall, acoustic levitation is poised to play a pivotal role in shaping advancements across science, medicine, and engineering, making it a technology worth exploring and developing further.

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DEVELOPMENT OF NEXT GENERATION STRETCHABLE MATERIALS FOR FLEXIBLE HYBRID ELECTRONICS(FHE)

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Abstract

This research focuses on the development of stretchable inks and z-axis adhesives for flexible hybrid electronics (FHE). The study involves fabricating a multilayer flashing LED on a thermoplastic polyurethane (TPU) substrate and analyzing its performance under various conditions, including tensile strain, humidity, and temperature variations. The findings reveal that silver-based materials maintain stable resistance under strain, whereas carbon-based materials exhibit better recovery. Additionally, environmental tests showed that silver-based samples experienced minimal resistance changes, while carbon-based samples stabilized after an initial drop. Furthermore, multilayer LED circuits encapsulated with an advanced formulation (Encapsulant B) demonstrated the highest durability against mechanical and environmental stressors.

Introduction

Flexible Hybrid Electronics (FHE) is an emerging technology that integrates traditional semiconductor components with flexible circuits, resulting in lightweight, bendable, and highly adaptable electronic systems. This innovation enables the development of electronics that conform to various surfaces, including the human body, making it ideal for applications in wearable health monitoring, industrial automation, structural health monitoring, environmental sensing, and agriculture.

The working principle of FHE involves printing conductive ink on a flexible substrate to form conductive traces that carry electrical signals. The integrated circuits (ICs) are manufactured separately using photolithography and later mounted onto the flexible substrate. This combination allows FHE to retain the processing power of traditional silicon electronics while offering several advantages, such as:

- Flexibility – Can bend and adapt to different surfaces.
- Lightweight Design – Reduces overall weight, enabling new form factors.
- High Performance – Provides the computational power of integrated circuits while maintaining flexibility.
- Cost-Effectiveness – More affordable compared to conventional silicon-based electronics.

A key challenge in advancing FHE technology is the development of next-generation stretchable materials that ensure reliable electrical connections, secure component attachment, and durable encapsulation to withstand mechanical and environmental stresses. This study explores the latest advancements in stretchable inks and pressure-less z-axis conductive epoxies, focusing on their reliability and durability under varying conditions such as elongation, strain, temperature, and humidity.
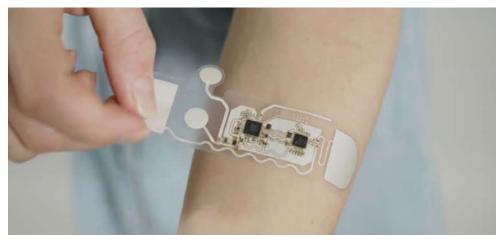
Fig. 1: Flexible Electronics [1]

Types of Stretchable materials

The development of stretchable materials plays a crucial role to achieve reliability in flexible hybrid electronics. These materials must maintain electrical conductivity while withstanding mechanical stress, making them essential for applications in wearable devices, healthcare monitoring, and industrial automation.

Stretchable materials in FHE can be broadly categorized into silver-based, carbon-based, and hybrid materials, each offering unique advantages in terms of conductivity, flexibility, and cost-effectiveness.

1) **Silver-Based Materials: High Conductivity and Performance**
   Silver is a widely used component in stretchable inks due to its exceptional electrical conductivity. These materials ensure minimal resistance changes under strain, making them ideal for high-performance electronic devices. Additionally, silver-based materials provide excellent flexibility, allowing circuits to endure repeated stretching and bending without significant degradation. However, their high cost remains a limitation, especially for large-scale applications.

2) **Carbon-Based Materials: A Cost-Effective Alternative**
   For applications requiring a balance between conductivity and affordability, carbon-based materials offer a viable solution. Made from carbon black or carbon nanotubes, these materials exhibit good electrical performance while being significantly cheaper than silver-based alternatives. While carbon-based inks may not achieve the same level of conductivity as silver, they excel in resistance recovery, meaning they regain conductivity after being stretched. This makes them particularly useful in applications where cost efficiency and durability are key considerations.

3) **Hybrid Materials: The Best of Both Worlds**
   To optimize both conductivity and cost, researchers have developed hybrid materials that combine silver and carbon-based components. These materials enhance electrical performance while reducing dependency on expensive silver-based inks. Hybrid materials are gaining traction in next-generation wearable sensors and flexible circuits, where durability and affordability are critical factors.

- **Choosing the Right Material: A Comparative View**
  When selecting a material for FHE applications, several factors come into play:
  1) Conductivity – Silver-based materials offer the highest conductivity, while carbon-based materials provide moderate conductivity with better cost efficiency.
  2) Flexibility – Both silver and carbon-based materials exhibit excellent flexibility, making them suitable for stretchable electronics.
  3) Cost – Silver-based materials are expensive, whereas carbon-based and hybrid materials offer a

more budget-friendly alternative.

The continued development of stretchable materials will play a key role in advancing wearable electronics, smart textiles, and next-generation medical devices. As research progresses, the focus will be on achieving the perfect balance between performance, durability, and affordability, ensuring that FHE technology reaches its full potential in real-world applications.

Fabrication Techniques for Stretchable Materials in Flexible Hybrid Electronics

The fabrication of stretchable materials is critical to the development of Flexible Hybrid Electronics (FHE), ensuring durability, conductivity, and flexibility. Key fabrication techniques include stretchable ink deposition, z-axis adhesives, and encapsulation, each contributing to the performance and structural integrity of FHE devices.

- **Stretchable Inks: Printing Conductive Layers**
  Stretchable inks create conductive pathways on flexible substrates. Common printing methods include:
  1) Screen Printing: Uses a mesh stencil to apply conductive ink uniformly.
  2) Inkjet Printing: Offers precise placement for fine, flexible circuits.
  3) Aerosol Jet Printing: Uses an ink mist for high-resolution, efficient deposition.
  These methods ensure that conductive traces remain functional under mechanical stress, making them ideal for wearable and stretchable electronics.
- **Z-Axis Adhesives: Ensuring Connectivity Between Layers**
  Z-axis adhesives are used to bond electronic components while maintaining electrical conductivity through the material's thickness. Key techniques include:
  1)Anisotropic Conductive Adhesives (ACA): Conducts electricity vertically while preventing short circuits.
  2) Isotropic Conductive Adhesives (ICA): Allows electrical connectivity in multiple directions for complex designs.
  These adhesives ensure strong interconnections that endure stretching and bending, essential for medical sensors, smart textiles, and flexible displays.
- **Encapsulation: Protecting Electronics from Environmental Stress**
  Encapsulation protects FHE devices from moisture, mechanical stress, and temperature fluctuations. Common materials include:
  1) Silicone: Offers elasticity and temperature resistance, ideal for stretchable applications.
  2) Polyurethane: Provides mechanical protection and flexibility, used in wearable tech.
  Encapsulation enhances the durability of FHE devices, ensuring reliable function in diverse environments.

Testing and Evaluation: Ensuring Reliability

Rigorous testing is crucial for validating the performance of stretchable materials. Key tests include:
- **Tensile and Strain Testing:** Assesses a material's ability to withstand stretching and deformation while maintaining functionality. This test is critical for wearable electronics and biomedical sensors.
- **Humidity and Temperature Testing:** Evaluates the impact of moisture and temperature variations on material performance. This ensures long-term reliability in real-world conditions, crucial for health monitoring devices, industrial sensors, and outdoor electronics.

As stretchable materials continue to evolve, advances in fabrication techniques, adhesive bonding, and encapsulation are paving the way for next-generation wearable technologies, smart textiles, and flexible

circuits. Ongoing improvements in testing and material durability promise to revolutionize industries, offering versatile, lightweight, and high-performance electronic solutions.

Future perspectives

The future of Flexible Hybrid Electronics (FHE) is bright, driven by both material innovations and the integration of advanced technologies like AI [3]. As researchers continue to push the boundaries of what stretchable materials can do, several key areas are expected to see rapid growth:

- **Material Innovation**: Ongoing developments in stretchable inks, encapsulants, and hybrid materials will further enhance the performance, durability, and cost-effectiveness of FHE. New formulations and combinations will not only improve mechanical stability but also enable more efficient energy usage, opening up possibilities for longer-lasting and more sustainable devices.
- **AI and Smart Electronics**: Artificial Intelligence (AI) is poised to play a significant role in FHE's evolution. By incorporating AI algorithms, future FHE devices could adapt to environmental changes in real-time. For example, wearable health monitors might use AI to analyze user data for early detection of health issues, or structural health sensors could autonomously adjust their sensitivity based on environmental conditions. AI could also assist in optimizing fabrication processes, making them faster, more efficient, and more scalable.
- **Integration Techniques**: As anisotropic conductive epoxies and other bonding materials evolve, they will enable even more reliable attachment of components to flexible substrates. This will make it possible to integrate FHE in more complex systems, such as smart packaging, robotics, and wearables, where seamless integration of flexible components with rigid electronics is critical.
- **Wearable Health Monitors:** The demand for wearable health devices is set to grow exponentially. As AI-driven analytics become more integrated, FHE will play an even bigger role in real-time health monitoring—tracking everything from vital signs to movement and posture, with the ability to analyze trends and even predict health issues before they become critical.
- **Structural Health Sensors:** The advanced durability and flexibility of next-generation FHE materials will be crucial in monitoring the health of infrastructure, such as bridges, buildings, and pipelines. By embedding FHE into the structure, AI could be used to predict maintenance needs, detect early signs of wear, and even automate responses to damage, preventing catastrophic failures.
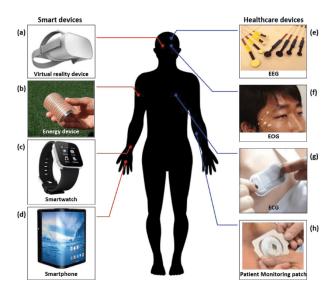

Fig. 2: Flexible Electronics for smart and healthcare devices [2]

Conclusion

The exploration of stretchable materials for Flexible Hybrid Electronics (FHE) has demonstrated substantial advancements, particularly in terms of durability, flexibility, and electrical conductivity. The study highlighted the promising potential of both silver-based and carbon-based materials, both of which exhibited excellent stretchability and recovery even under strain. Among the key findings, Encapsulant B, a newly developed material, stands out for its exceptional ability to protect FHE circuits. This novel encapsulant was found to offer superior mechanical and environmental stress resistance, significantly enhancing the longevity and functionality of FHE devices.

In tests, Encapsulant B-encapsulated samples outperformed others, particularly in tensile and strain cycling tests, showcasing its potential for ensuring long-term stability in real-world applications. The findings underline the vital role that material innovations like Encapsulant B will play in shaping the future of flexible electronics. With continued development in these areas, Flexible Hybrid Electronics are poised to revolutionize industries such as wearable health technology, structural health monitoring, and more, delivering reliable, durable, and flexible solutions across a wide range of applications.

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COMMUNICATION

HIGH-SPEED MULTIMEDIA STREAMING USING INDOOR VISIBLE LIGHT COMMUNICATION

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Abstract

High-quality real-time multimedia streaming is achieved over a laser-based indoor visible light communication (VLC) link. The system features a blue laser diode with remote phosphor as a transmitter and an amplified AC-coupled silicon photodetector as a receiver, utilizing Universal Software Radio Peripheral (USRP) platforms for modulation and demodulation. The VLC link, with a bandwidth exceeding 800 MHz, delivers an Ethernet data rate of 200 Mbps and a radio frequency carrier of 245 MHz. Leveraging the inherent bandwidth of laser sources, this method surpasses the limitations of LED-based VLC systems, enabling low-latency, data-intensive applications such as secure high-bandwidth communication in robotic telepresence and tactile operations.

Introduction

The increasing demand for high-speed wireless communication has pushed the limits of traditional radio frequency (RF) communication systems. With the rapid expansion of the Internet of Things (IoT), smart devices, and high-definition multimedia applications, existing RF spectrum resources are becoming congested. Additionally, RF-based communication faces challenges such as interference, security vulnerabilities, and spectrum scarcity.

To address these issues, researchers have explored alternative wireless technologies, including millimeter-wave (mmWave) communication, terahertz (THz) communication, and optical wireless communication (OWC). Among these, visible light communication (VLC) has emerged as a promising solution due to its wide bandwidth, low power consumption, and high security.

VLC utilizes visible light (380–750 nm) emitted by LEDs (Light-Emitting Diodes) or LDs (Laser Diodes) to transmit data while simultaneously providing illumination. However, LED-based VLC systems are limited in bandwidth (20 MHz), which restricts their data transmission capabilities. To overcome this limitation, laser diodes (LDs) have been proposed as an alternative light source, offering higher modulation bandwidth (>800 MHz) and supporting gigabit-per-second data rates, making them highly suitable for real-time high-definition multimedia streaming.

Fundamentals of Visible Light Communication (VLC)

- Visible Light Communication (VLC) is a subset of Optical Wireless Communication (OWC) that operates within the visible spectrum (380–750 nm). It employs light sources (LEDs or LDs) to encode data signals, which are then detected and decoded at the receiver end. The basic principle involves:
- Modulation - The data signal is modulated onto the intensity of the light source.
- Transmission – The modulated optical signal propagates through free space.
- Reception & Demodulation – A photodetector captures the optical signal and converts it into an electrical signal for data recovery.
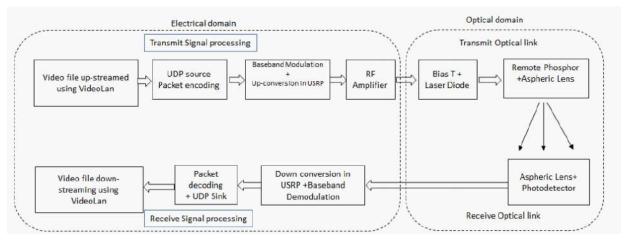
Fig. 1: Key stages of experimental setup for multimedia streaming [1]

Key Advantages of VLC Over RF

- Higher bandwidth – Operates in the THz frequency range, enabling gigabit data rates.
- No RF interference – VLC signals do not interfere with RF-based systems like Wi-Fi or Bluetooth.
- Improved security – Visible light signals do not penetrate walls, reducing the risk of eavesdropping.
- Energy efficiency – LED and LD sources serve a dual purpose: illumination and communication.

System Architecture and Experimental Setup

To evaluate the feasibility of laser-based VLC for multimedia streaming, an experimental testbed was developed. The system consists of a transmitter, a receiver, and a signal processing unit.

- Transmitter Design: The VLC transmitter converts the digital data stream into an optical signal using a high-speed laser diode (LD).
- Laser diode (LD): A 450 nm blue laser diode (Osram PL450B, 80 mW) is used as the optical source.
- Modulation circuit: The data signal is modulated onto the laser intensity using On-Off Keying (OOK) and Gaussian Mean Shift Keying (GMSK).
- Remote phosphor (Ce:YAG): Converts blue laser light into white light to enable simultaneous illumination.
- Receiver Design: The receiver captures and processes the transmitted optical signals using a high-speed photodetector.

- Photodetector (PD): A Menlo Systems FPD310FV silicon photodetector is used to detect laser signals.
- Amplifier & signal processing: An AC-coupling circuit filters noise and boosts signal strength before demodulation.
- USRP-based signal processing: A Universal Software Radio Peripheral (USRP) module is used for real-time signal decoding.
- Data Transmission & Modulation Techniques
- On-Off Keying (OOK) – Simple digital modulation where light ON represents '1' and OFF represents '0'.
- Gaussian Mean Shift Keying (GMSK) – A spectrally efficient modulation technique reducing inter-symbol interference. The modulated signals are transmitted via a laser beam and captured at the receiver, where they are demodulated and reconstructed for real-time multimedia playback. The Photograph of the experimental setup of VLC testbed for multimedia streaming 2.
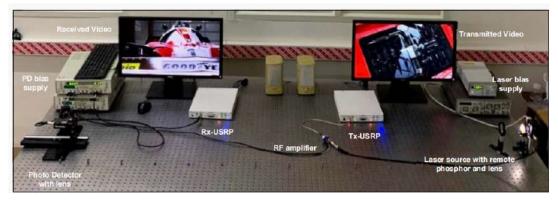

Fig. 2: Photograph of the experimental setup of VLC testbed for multimedia streaming [1]

Performance Evaluation and Experimental Results

The system's performance was evaluated using several key metrics, including bandwidth, data rate, video quality, and reliability. The analysis was focused on understanding how well the system could support high-speed data transmission, real-time video streaming, and overall reliability under different conditions.

- Bandwidth and Data Rate Analysis: The measured bandwidth for the system exceeded 800 MHz, which is significantly higher than the bandwidth of traditional LED-based VLC systems, which typically operate around 20 MHz. This substantial increase in bandwidth allows for a much greater capacity to transmit data. The system achieved data rates of up to 1 Gbps, which is crucial for applications requiring high-speed data transmission, such as HD video streaming. With this high data rate, the system can deliver seamless HD video content without interruptions or delays.
- Real-Time Video Streaming Performance: The system was tested for its ability to handle real-time video streaming. A 1280×720 HD video stream was transmitted over the VLC link. To assess the performance, the Ethernet transmission rate was measured at 200 Mbps, ensuring that the video data could be transmitted with minimal buffering. Additionally, the system showed low frame drop rates, especially when operating at higher optical power levels. This means that even under challenging conditions, such as variations in light intensity or environmental interference, the video stream maintained high quality, with minimal interruptions or frame loss.
- Impact of Carrier Frequency on Performance: Carrier frequency plays a significant role in the overall performance of the VLC system. When higher RF carrier frequencies, such as 245 MHz, were used,

the system demonstrated improved performance in terms of data transmission rates and video quality. This is because higher frequencies provide better modulation capabilities and can carry more data over the same bandwidth. Conversely, lower carrier frequencies resulted in higher bit error rates (BER), which led to a degradation in video quality. As the bit error rate increases, the system struggles to maintain the integrity of the transmitted data, leading to a noticeable reduction in the video quality (e.g., pixelation, blurriness, or buffering).

The Experimentally measured frequency response of the VLC link and BER as a function of transmitted power 3.
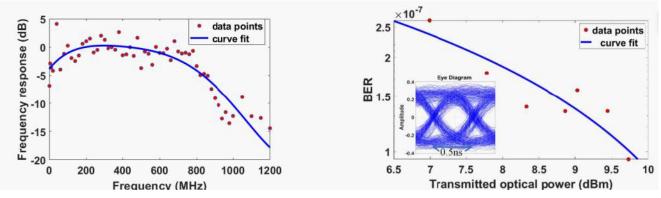

Fig. 3: . Experimentally measured frequency response and BER [1]

Applications of Laser-Based VLC Systems

Smart Indoor Wireless Networks are evolving to meet the growing demand for high-speed, low-latency connectivity, especially in environments like homes, offices, and commercial spaces. These networks combine visible light communication (VLC) and Wi-Fi, creating a hybrid system that leverages the strengths of both technologies.

- Hybrid VLC and Wi-Fi Networks: By integrating VLC (which uses light for communication) and traditional Wi-Fi, smart indoor wireless networks can provide seamless connectivity across different use cases. While Wi-Fi continues to be a popular choice for long-range wireless communication, VLC offers a unique advantage with its ability to deliver faster data transmission and lower latency, especially when combined with Wi-Fi. This combination ensures that users experience reliable and high-speed connections no matter where they are inside a building.
- Li-Fi-Based Smart Lighting: One of the exciting aspects of this hybrid network is the use of Li-Fi (Light Fidelity) technology. Li-Fi is a form of VLC that uses light emitted from LED bulbs to transmit data at high speeds. Smart lighting solutions, powered by Li-Fi, not only enhance the ambiance and energy efficiency of indoor spaces but also improve communication capabilities. This allows for a more immersive experience in settings like homes and offices, where wireless data is transmitted via the same light fixtures that provide illumination.
- High-Speed Multimedia Streaming: The adoption of this hybrid network infrastructure is particularly beneficial for high-bandwidth applications like 4K/8K video streaming, which require ultra-low latency for a seamless experience. By utilizing VLC's high-speed data rates, these networks can support high-definition video streaming without buffering, even in crowded environments. This also opens doors to immersive technologies like Augmented Reality (AR) and Virtual Reality (VR), which demand both fast data transmission and minimal delays for optimal user experience. VLC, with its higher data rates, makes these technologies more feasible and accessible in indoor settings.

- Secure Communication Systems: VLC also plays a crucial role in enhancing the security of communication systems. Unlike traditional radio frequency (RF) systems, VLC is confined to the space where the light is visible, making it harder to intercept. This makes VLC ideal for sensitive applications in sectors such as military communications, where security risks associated with RF-based systems (e.g., eavesdropping or jamming) are a concern. VLC's directional nature offers an additional layer of security, as signals are confined within a defined space.

Conclusion

Major challenges in Visible Light Communication (VLC) include multipath effects, where reflections from walls cause signal distortion, and the requirement for a line-of-sight (LOS) for uninterrupted communication, as blockages in the transmission path can disrupt the signal. Additionally, laser safety concerns arise, as eye protection is necessary when using high-power laser diodes (LDs). Future research in VLC focuses on advanced modulation schemes like OFDM and MIMO to enhance spectral efficiency, as well as machine learning techniques to create adaptive systems that optimize link performance. Hybrid VLC-RF systems are also being explored to ensure seamless wireless communication. In conclusion, this paper highlights a high-speed, laser-based VLC system capable of real-time multimedia streaming, achieving gigabit data rates with significantly higher bandwidth than LED-based systems. The experimental results demonstrate that laser-based VLC holds promise as a solution for future wireless networks, smart environments, and high-definition video applications. With further advancements in modulation, AI-based optimization, and hybrid systems, VLC has the potential to revolutionize next-generation 5G/6G wireless networks.

Acknowledgement

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DEVELOPMENT OF WIRELESS DATA COMMUNICATION FOR IMPLANTABLE ARTIFICIAL HEARTS

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Abstract

Wireless data communication plays a crucial role in monitoring artificial hearts while minimizing infection risks. Traditional methods, such as electromagnetic induction and optical transmission, often struggle with alignment issues, making data transmission unreliable when external devices shift[1]. To address these challenges, this study explores the development of a Bluetooth-based ultra-high-frequency (UHF) wireless communication system for stable and efficient data transfer. The system consists of an internal transmission unit implanted in the body and an external unit that receives and processes the data. Experiments conducted with pig meat to simulate human tissue demonstrated stable transmission at 20 kbps within a 10-meter range. These findings confirm that Bluetooth technology offers a reliable, non-invasive, and continuous monitoring solution for patients with artificial hearts, enhancing mobility and reducing medical complications.

Introduction

Artificial hearts have become an essential solution for patients with severe heart failure, replacing or assisting natural cardiac function. Long-term monitoring of artificial heart performance and the patient's physiological condition is critical for ensuring optimal treatment. Traditional monitoring techniques used in Intensive Care Units (ICU) rely on invasive measurement methods, making them unsuitable for continuous long-term use.

To overcome this limitation, researchers have developed Smart Artificial Heart (SAH) technology, which integrates non-invasive sensors and a remote monitoring system. However, transmitting this data wirelessly remains a challenge due to the limitations of existing wireless methods, such as electromagnetic induction and optical transmission[2]. These systems often require precise alignment of the external data transmission unit, making data transfer unstable if the unit shifts position.

This study focuses on developing a wireless communication system based on Bluetooth technology to ensure reliable, high-speed, and secure data transmission between an implantable artificial heart and an external monitoring device[3]. By leveraging ultra-high-frequency (UHF) radio waves, the system allows continuous non-contact data transfer, eliminating the need for physical alignment of external units.

System Design and Development

The advancement of artificial heart technology necessitates a reliable wireless data communication system for real-time monitoring and control in fig [1]. This paper presents a system comprising an implantable module, an external receiver, and a cloud-based monitoring system, using protocols like BLE, NFC, MICS, and UWB for efficient data transmission. Power management is optimized through energy harvesting, low-power microcontrollers, and duty cycling. Security measures include end-to-end encryption, authentication, and anomaly detection[2]. Prototype testing confirms reliable communication with minimal power consumption. Future work includes further miniaturization and AI-driven predictive analytics for improved patient outcomes.
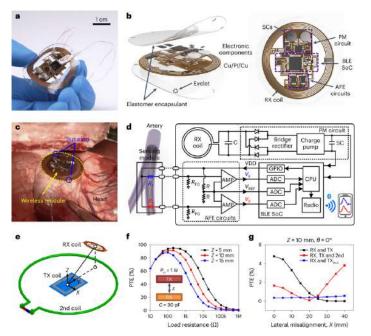
Fig. 1: Subcutaneous implants for wireless power and data transmission an optical image (Courtesy : ResearchGate)

Design Requirements

A successful wireless communication system for implantable artificial hearts must meet several key requirements:

- **Compact Size:** The internal transmission unit must be small enough for implantation (no larger than 70 mm × 100 mm × 10 mm).
- **Stable Communication:** Data transfer must function within a distance of at least 3 meters, allowing patient mobility without the need for close external monitoring devices.
- **Sufficient Transmission Speed:** The system must transmit at a minimum of 9.6 kbps to support real-time monitoring of six key physiological sensors.
- **Minimal Electromagnetic Interference:** The system must operate without disrupting other medical devices or being affected by external signals.
- **Low Power Consumption:** Energy efficiency is crucial to avoid excessive battery drain, ensuring the artificial heart functions without disruption.

Selection of Wireless Technology

Several wireless communication technologies operate in the 2.45 GHz industrial, scientific, and medical (ISM) frequency band, including Wi-Fi, ZigBee, and Bluetooth[3]. Bluetooth technology was chosen for this system due to its:

- **Reliable Data Rate:** Bluetooth supports speeds up to 3 Mbps, ensuring stable transmission.
- **Security Features:** It includes encryption, device authentication, and error detection to protect sensitive medical data.
- **Low Power Consumption:** Bluetooth consumes minimal energy, making it ideal for battery-powered medical implants.
- **Ability to Penetrate Soft Tissue:** Unlike optical transmission, Bluetooth signals can pass through human tissue without requiring direct line-of-sight alignment.

Prototype Development and Testing

A prototype wireless communication system for artificial hearts was developed and tested, comprising an implantable module, an external receiver, and a cloud-based monitoring system[1]. The system utilized BLE, NFC, MICS, and UWB for efficient data transmission while optimizing power management through energy harvesting, low-power microcontrollers, and duty cycling. Security measures, including encryption, authentication, and anomaly detection, ensured secure data transfer. Testing confirmed reliable communication with minimal power consumption, validating its suitability for long-term implantation. Future work will focus on further miniaturization and AI-driven predictive analytics for enhanced patient outcomes.

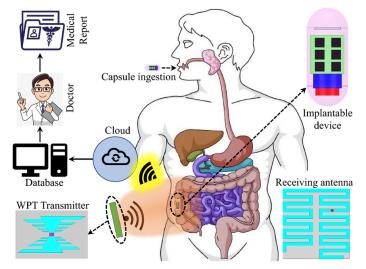Fig. 2: Generalized wireless power transfer WPT system for deep implanted biomedical devices (Courtesy : Nature)

System Components

The wireless communication system consists of two main units:

- **Internal Transmission Unit:** Implanted inside the patient, it features a microcontroller with an 8-channel 10-bit A/D converter and a Bluetooth module to send real-time sensor data.

- **External Transmission Unit:** Positioned outside the body, it receives Bluetooth signals and forwards the data to a computer via an RS-232C connection for further processing.

Performance Testing

To assess system performance, the internal unit was wrapped in pig meat to simulate human tissue[3]. The study tested three conditions:
- No tissue covering (0 mm thickness)
- Thin tissue layer (1.5 mm)
- Thicker tissue layer (3 mm)

The internal unit was then secured to a test subject's abdomen to examine the effects of body positioning on signal quality. Two test setups were used:
- **Direct Line of Sight:** The internal and external units were aligned without obstruction.
- **Obstructed Signal Path:** The subject's body blocked the direct path between the units.

Results and Observations

Data transmission remained stable under all conditions:
- With direct line-of-sight, speeds consistently exceeded 55 kbps, even with 3 mm tissue coverage[1].
- With obstructed transmission, speeds decreased to 20 kbps but remained functional over a 10-meter range.

These results confirm that Bluetooth-based wireless communication ensures reliable and stable data transfer, even when body movement interferes with the signal path.
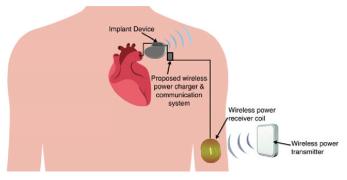
Fig. 3: Implanted heart(Courtesy : ResearchGate)

Discussion and Future Improvements

This research confirms that Bluetooth-based UHF communication provides a stable, high-speed, and secure alternative to traditional electromagnetic induction and optical transmission methods for implantable artificial hearts[3]. The key advantages include:
- **Minimized Infection Risk:** Eliminates the need for physical connectors, reducing the chance of infections.
- **Enhanced Patient Mobility:** The system functions within a 10-meter range, allowing patients to move freely without external unit constraints.

- **Reliable Data Transfer:** Even with soft tissue interference, the system maintains adequate transmission speeds.

Challenges and Future Enhancements

- **Miniaturization:** Future versions should reduce the size of the internal unit by using smaller electronic components.
- **Extended Testing:** Further research is needed to determine the maximum tissue thickness that allows stable transmission.
- **Regulatory Compliance:** The system must meet Specific Absorption Rate (SAR) safety standards for electromagnetic exposure.
- **Integration of Bluetooth 3.0 and Low Energy (LE):** These versions can improve power efficiency and data transfer rates.
- **Self-Recovery Mechanisms:** Future versions may incorporate self-recovery mechanisms to handle temporary connection failures, ensuring uninterrupted monitoring.

Conclusion

This study successfully developed a Bluetooth-based wireless data communication system for implantable artificial hearts. The system enables continuous, non-invasive data transmission from inside the body to external monitoring devices, overcoming the limitations of electromagnetic induction and optical transmission.

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LASER BASED COMMUNICATION

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Abstract

Laser-based communication is a cutting-edge wireless network technology that utilizes light rather than radio frequencies to transmit information. This system, characterized by its cost-effectiveness, low power consumption, compact hardware[4], and immunity to electromagnetic interference, is ideal for point-to-point communication. It employs two parallel laser beams, one for transmission and the other for reception, to enable two-way communication. The technology works by amplifying a voice signal, converting it into a light signal using a laser diode, and transmitting it through free space to a receiver equipped with a Light Dependent Resistor or photodiode. This signal is then reconverted into an electrical format for further processing. The seminar explores the system's working principles, advantages such as high speed (over 1 Gbps), low error rates, and secure, interference-free operation, as well as its limitations, including sensitivity to atmospheric conditions like rain and fog. Applications span from defense and aerospace to mass communication and real-time data transmission in space exploration. The future scope emphasizes its potential for faster data transfer, enhanced deep-space communication, and integration into high-definition imaging systems.

Introduction

Laser-based communication is a cutting-edge wireless technology that uses modulated laser beams to transmit data, offering a compelling alternative to traditional radio frequency (RF) systems. This report delves into the fundamentals, advantages, and challenges of this technology, which is characterized by high data rates, low power consumption, and immunity to electromagnetic interference. By leveraging narrow beamwidths, laser systems ensure secure and high-speed point-to-point communication, making them ideal for applications in defense, telecommunications, and space exploration.

This seminar report outlines the working principles of laser communication systems[3], highlighting their components and mechanisms, such as laser diodes for data transmission and photodiodes for signal reception. The report also examines the operational challenges posed by environmental factors like fog, rain, and misalignment, alongside emerging solutions such as adaptive optics and error correction techniques. Furthermore, it explores the diverse applications of laser-based systems, ranging from inter-satellite communication to secure urban data links and real-time space exploration missions.

As the demand for efficient and secure communication grows, laser-based systems are positioned to play a pivotal role in shaping the future of data transfer across terrestrial and extraterrestrial domains. This report aims to provide a comprehensive understanding of the technology's potential and its trajectory in revolutionizing global communication networks[1].
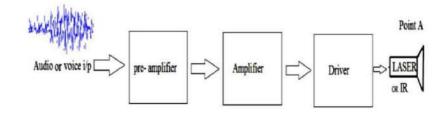
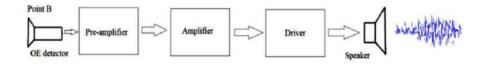Figure 1. Transmitter section of LASER Communication

Figure 2. Receiver section of LASER Communication

Fig. 1: Key stages of Generative AI In Cyber Security[1]

Working of Transmitter Section

A laser-based communication transmitter circuit is a system designed to transmit audio or other electrical signals wirelessly using light as the transmission medium. The process begins with an input signal, such as an audio signal from a microphone or an audio jack[5]. This signal is relatively weak and needs to be amplified for effective transmission. The first stage of amplification is achieved using a transistor-based pre-amplifier, which boosts the signal to an intermediate level. This is followed by a second stage of amplification, which further increases the signal strength to achieve the overall gain required for reliable transmission.

Once the electrical signal is sufficiently amplified, it is fed into a driver circuit connected to a laser diode. The driver circuit ensures that the amplified signal is appropriately modulated and matches the operational requirements of the laser diode. The laser diode acts as the core component for converting the electrical signal into a light signal. This light signal carries the information contained in the original audio or electrical input.

The light signal generated by the laser diode is modulated, meaning it varies in intensity or other properties according to the input signal. This modulated light acts as the carrier wave for the transmitted information. The transmission occurs through free space, where the laser beam propagates to the receiving end[1]. The use of a laser provides high precision and minimal dispersion, making it ideal for point-to-point communication over long distances. This technology is widely used in free-space optical communication systems, offering advantages such as immunity to electromagnetic interference and high data transfer rates.
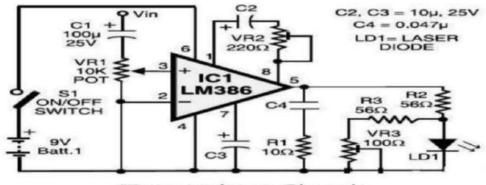
Working of Reciever Section

A laser-based communication receiver circuit is designed to capture and process the modulated light signal transmitted by the laser-based transmitter. The process begins when the modulated light signal from the laser reaches the receiver side[3]. Here, the light signal is detected by a photodetector, typically a Light Dependent Resistor (LDR) or a photodiode. These devices are sensitive to light and can convert the intensity of the incoming light back into an electrical signal[4]. The amount of light received directly correlates to the strength and modulation of the transmitted signal.

Once the light signal is captured and converted into an electrical signal, it typically needs to be amplified to restore the strength lost during transmission and to bring it into an audible range if it is an audio signal. This is achieved by passing the electrical signal through an amplifier stage, which boosts the signal to the necessary level for further processing.

Finally, the amplified electrical signal is ready to be output. If the transmitted signal was an audio signal, it can be sent to a speaker or any other audio-processing device, where it is converted back into sound[2]. If the signal contained data, it would be processed by a computer or another type of receiver capable of interpreting and using the information. The entire process ensures that the originally transmitted information, whether audio or data, is accurately received, amplified, and outputted in a usable format, enabling effective communication through the laser-based system. This type of communication is highly efficient, with minimal electromagnetic interference, and is used in a variety of applications such as wireless audio transmission, data communication, and optical networks.

Fig. 2: Transmitter Circuit

Fig. 3: Reciever Circuit

Advantages

- **High Speed**: Capable of speeds exceeding 1 Gbps, surpassing traditional LAN or wireless LAN networks.
- **Ease of Deployment**: Quick and straightforward to set up.
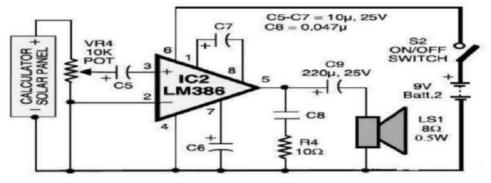- **Immunity to Electromagnetic Interference**: Operates without disruptions from electromagnetic sources.
- **Low Power Requirement**: Energy-efficient system.
- **High Bit Rates and Low Error Rates**: Enables reliable and fast data transmission.
- **Security**: Narrow laser beams offer increased security against interception.
- **No Licensing Required**: Operates license-free over long distances, unlike many radio communications.
- **Protocol Transparency**: Works seamlessly with existing communication protocols.
- **Full Duplex Operation**: Supports simultaneous two-way communication.
- **No Fresnel Zone Required**: Simplifies the system design by eliminating certain constraints.

Disadvantages

- **Beam Dispersion**: Loss of signal strength over longer distances due to beam spread.
- **Atmospheric Challenges**: Affected by environmental factors such as:
  - **Rain**: Significant signal attenuation.
  - **Fog**: High attenuation (10–100 dB/km).
  - **Snow**: Impacts reliability.
  - **Pollution/Smog**: Reduces clarity of the laser beam.
- **Interference**: Background light sources like the sun can interfere with signal reception.
- **Shadowing**: Physical obstructions can block the beam path.
- **Pointing Stability**: Wind and other factors can cause misalignment of the beam.
- **Scintillation**: Variations in air density affect signal quality.

Future of Laser Based Communication

The future scope of laser-based communication is highly promising as advancements in technology continue to address current limitations and unlock new possibilities. This system is poised to revolutionize global communication networks by enabling high-speed data transfer, enhanced security, and minimal interference. Emerging applications include interplanetary internet for space exploration, ultra-high-speed global 5G and beyond networks, and secure quantum communication systems leveraging quantum key distribution. Free-space optical communication networks and underwater laser systems are expected to provide robust solutions for connectivity in rural, urban, and marine environments. Additionally, the integration of laser communication in automotive systems, industrial automation, medical applications, and augmented reality (AR)/virtual reality (VR) devices highlights its transformative potential. These advancements, along with innovations in miniaturization and adaptive technologies, will enable laser-based communication to play a pivotal role in smart cities, advanced robotics, and real-time data-intensive operations, solidifying its position as a cornerstone of future communication infrastructures.

Conclusion

Laser communication technology represents a transformative advancement, addressing many limitations of traditional systems by offering high-speed, secure, and interference-resistant data transmission. With features like minimal power consumption, low latency, and immunity to electromagnetic interference, laser communication is particularly suited for applications in urban infrastructure, secure defense operations, and complex space missions. Its narrow beamwidth enhances security by making data transmission difficult to intercept, and its high data rates, exceeding 1 Gbps, support bandwidth-intensive tasks such as HD video streaming and massive file transfers.Despite its advantages, laser communication faces challenges such as atmospheric interference from fog, rain, and snow, which can degrade signals over long distances, and the difficulty of maintaining precise alignment between transmitters and receivers in dynamic outdoor environments. Furthermore, ambient light interference, such as sunlight, can distort signals during daylight operations. To address these issues, ongoing research is developing solutions like adaptive optics to counteract atmospheric turbulence, auto-alignment mechanisms for maintaining precision, and advanced error-correction techniques to ensure data integrity.As these technologies mature, laser communication is poised to become an indispensable part of modern networks. Its unique combination of speed, security, and resilience positions it as a critical enabler for diverse applications, from inter-building connections in urban areas to secure military communications and pioneering space exploration initiatives. By overcoming current limitations, this technology is set to revolutionize global communication, bridging gaps in conventional systems and unlocking new possibilities for high-performance data transmission.

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QUANTUM COMMUNICATION : REVOLUTIONIZING SECURE DATA TRANSMISSION

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Abstract

Quantum communication is an emerging technology that leverages the principles of quantum mechanics to ensure highly secure data transmission. Unlike classical communication systems, which rely on conventional encryption methods, quantum communication utilizes quantum key distribution (QKD) to enable unbreakable encryption by exploiting the properties of quantum entanglement and superposition. This technology is revolutionizing fields such as cybersecurity, financial transactions, defense communications, and satellite-based global connectivity. Recent advancements have led to the successful implementation of quantum communication networks across various sectors, addressing critical challenges such as data interception and cyber threats. This paper explores the fundamental concepts of quantum communication, its applications in real-world scenarios, and the potential it holds for shaping the future of secure information exchange.

Introduction

Quantum communication is an emerging technology that leverages the principles of quantum mechanics, such as superposition and entanglement, to enable highly secure and efficient data transmission[1]. Unlike traditional systems that rely on binary bits (0s and 1s), quantum communication utilizes qubits, which can exist in multiple states simultaneously.
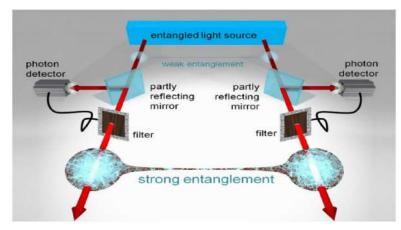

Fig. 1: Schematic of the Distillation of Quantum Entanglement by Subtracting Photons in the Signals [1]

The key advantage of this technology is its security. Any attempt to intercept quantum communication disturbs the system, making eavesdropping immediately detectable. This makes it a groundbreaking solution for secure communication in sectors like defense, finance, and healthcare.

Key Components of Quantum Communication

Quantum communication relies on several key technologies that ensure secure and long-distance data transfer. The major components include:

- **Quantum Key Distribution (QKD):** QKD allows two parties to securely share encryption keys. It ensures that any interception attempt alters the quantum state, alerting the users. The BB84 protocol is one of the most widely used methods for QKD.
- **Quantum Repeaters:** Overcoming distance limitations, quantum repeaters help extend communication signals over long distances without losing their quantum properties[3]. They play a crucial role in enabling large-scale quantum networks.
- **Satellite-Based Quantum Communication:** Quantum communication via satellites allows secure data transmission over vast distances. Countries like China have demonstrated successful satellite-based QKD, achieving secure links between continents.
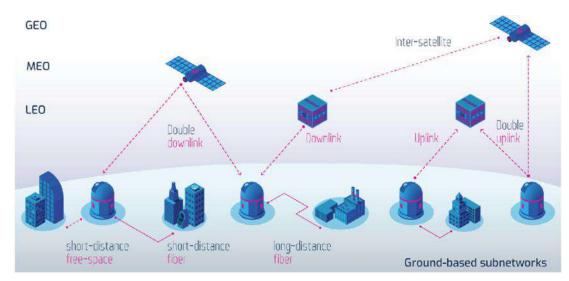
Fig. 2: Diagram illustrating the QKD process or satellite-based communication [2]

Applications of Quantum Communication

The potential applications of quantum communication span across various industries, enhancing data security and opening new possibilities:

- **Unhackable Networks:** Organizations such as banks, military institutions, and healthcare providers can benefit from the secure exchange of sensitive information without the risk of cyberattacks.
- **Quantum Internet:** A future global quantum internet would allow quantum computers to connect securely, enabling advanced computations and problem-solving capabilities beyond classical networks[2].
- **Secure IoT Communication:** As the Internet of Things (IoT) expands, quantum encryption can ensure secure connections between smart devices, protecting them from potential cyber threats.
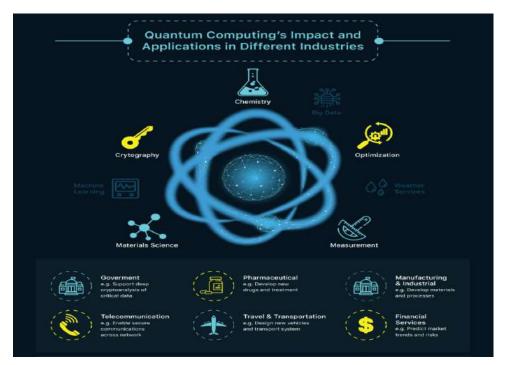
Fig. 3: Infographic showcasing different applications of quantum communication in real-world scenarios [3]

Challenges in Quantum Communication

Despite its promising potential, several challenges hinder the widespread adoption of quantum communication:

- **High Costs:** Developing and maintaining quantum systems is expensive, limiting their adoption to research institutions and governments.
- **Technological Limitations:** Quantum communication requires highly sensitive and stable hardware, such as photon detectors and quantum memory, which are still under development[3].
- **Environmental Sensitivity:** Quantum states are fragile and can be easily affected by environmental factors like temperature fluctuations and noise, making implementation challenging.

Addressing these challenges requires continued investment in research and development to make quantum communication more practical and accessible.

Future Prospects and Conclusion

The future of quantum communication looks promising, with continuous advancements in quantum computing and cryptography. Governments and private companies are investing heavily in quantum technology, aiming to create secure global communication networks.

In the coming years, we can expect to see wider adoption of quantum communication in industries requiring high levels of security. With improvements in infrastructure and affordability, this technology will redefine data security standards worldwide.

As research progresses, quantum communication could become an integral part of our daily lives, ensuring a safer and more connected world.

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ELECTRIC VEHICLE

ADVANCEMENTS AND CHALLENGES IN COMMERCIAL ELECTRIC VEHICLE CHARGING INFRASTRUCTURE

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Abstract

The rapid transition to commercial electric vehicles (CEVs) represents a pivotal step toward achieving global sustainability goals by reducing carbon emissions and enhancing energy efficiency in transportation. However, the widespread adoption of CEVs is contingent upon the development of robust and scalable charging infrastructure. This paper presents a comprehensive analysis of existing charging models, including return-to-base charging, on-route fast charging, and battery-swapping stations, evaluating their feasibility for commercial fleets. Key challenges such as grid stability, high electricity demand, economic viability, and policy constraints are explored, alongside emerging solutions like Vehicle-to-Grid (V2G) technology, smart charging strategies, and advancements in high-power fast charging. Additionally, the paper outlines potential future directions for commercial EV infrastructure development, emphasizing the need for a collaborative approach involving policymakers, industry leaders, and technology innovators. By addressing these challenges, the evolution of CEV infrastructure can accelerate, ensuring a seamless and efficient transition to an electrified transportation ecosystem.

Introduction

The electrification of commercial transportation is gaining significant momentum as industries and governments worldwide aim to curb greenhouse gas emissions and mitigate climate change. The transportation sector remains a major contributor to global carbon emissions, with commercial vehicles accounting for nearly 40% of total road transport emissions. The shift to electric commercial fleets, particularly medium- and heavy-duty trucks, holds immense potential for reducing fuel dependency, lowering operational costs, and promoting sustainability. Despite these advantages, the large-scale adoption of commercial EVs faces significant challenges [2], primarily centered around charging infrastructure. Unlike passenger EVs, commercial vehicles require higher energy input, faster charging solutions, and strategically located infrastructure to align with their operational schedules. The two primary charging models—return-to-base charging at fleet depots and on-route charging at public stations—offer different benefits and limitations. While return-to-base charging enables centralized energy management, it imposes high costs on fleet operators due to the need for dedicated charging stations and grid reinforcements. On the other hand, on-route charging necessitates widespread deployment of high-power fast chargers, posing logistical and economic challenges.

Additionally, innovations such as Vehicle-to-Grid (V2G) integration provide an opportunity to enhance grid stability and optimize energy distribution. However, practical implementation requires overcoming

technical constraints, regulatory barriers, and cost concerns. This paper explores the current state of commercial EV charging infrastructure, identifies key obstacles, and discusses future advancements necessary to facilitate widespread adoption. Through a comprehensive review of charging technologies, economic considerations, and policy frameworks, this study aims to contribute to the development of a sustainable and scalable charging network for commercial electric vehicles.

Need for a Robust Charging Infrastructure

The transition from internal combustion engine (ICE) commercial vehicles to electric alternatives is accelerating due to environmental concerns, government regulations, and advancements in battery technology. However, one of the most significant barriers to widespread adoption is the lack of a well-developed charging infrastructure. Unlike passenger electric vehicles, commercial EVs—particularly medium- and heavy-duty trucks—have distinct charging requirements due to their larger battery capacities, higher energy consumption, and operational constraints.

Commercial fleet operators must consider multiple factors when adopting EVs, including charging time, station availability, and grid capacity[4]. The success of electrifying commercial transportation depends on a scalable and efficient charging infrastructure that minimizes downtime while maximizing energy efficiency.

Developing such infrastructure requires addressing several challenges:

- **High Energy Demand:** Commercial EVs require significantly more power than passenger EVs, necessitating high-capacity chargers.
- **Charging Speed:** Fast-charging solutions must be deployed to avoid operational delays and revenue loss.
- **Grid Stability:** Large-scale EV charging can put stress on the power grid, requiring smart energy management strategies.
- **Strategic Station Placement:** Charging locations must be optimized based on fleet routes to ensure accessibility without causing disruptions.

To overcome these obstacles, industry leaders and policymakers must collaborate to develop innovative charging solutions, including fast-charging networks, battery-swapping stations, and Vehicle-to-Grid (V2G) integration. The following sections explore the various charging models available for commercial EVs, their advantages, challenges, and the future direction of charging infrastructure development.

Charging Infrastructure for Commercial Electric Vehicles

The adoption of commercial electric vehicles (CEVs) relies heavily on the availability of efficient and scalable charging infrastructure. Unlike passenger EVs, commercial vehicles have higher energy demands and stricter operational constraints, requiring specialized charging strategies. There are three primary charging models for CEVs, each with its own advantages and challenges.

1. Return-to-Base Charging

In this model, commercial vehicles charge at dedicated fleet depots or company-owned facilities[1]. This approach is widely used for fleets operating in a fixed geographic region, such as delivery trucks, municipal vehicles, and logistics fleets.

Advantages:

- **Predictability:** Vehicles have a fixed schedule, allowing for optimized charging management.
- **Cost Efficiency:** Centralized charging reduces reliance on expensive public charging stations.

- **Grid Integration:** Fleet operators can implement load balancing, demand response, and off-peak charging strategies to minimize electricity costs.

Challenges:
- **High Infrastructure Costs:** Establishing a dedicated charging depot requires significant capital investment.
- **Grid Impact:** Simultaneous charging of multiple vehicles can strain local power grids, necessitating upgrades.
- **Limited Flexibility:** Vehicles must return to base for charging, which may not be feasible for long-haul operations.

2. On-Route Public Charging

Public charging stations are essential for commercial fleets that travel long distances, such as freight trucks and ride-hailing services[5]. These stations provide fast-charging solutions at key locations like highways, logistics hubs, and urban centers.

Advantages:
- **Extended Range:** Enables long-haul CEVs to operate without range anxiety.
- **Shared Infrastructure:** Reduces fleet operator investment in private charging depots.
- **Scalability:** A well-distributed public network can accommodate diverse commercial vehicle types.

Challenges:
- **Charging Time:** Even fast chargers require downtime, impacting vehicle productivity.
- **Grid Demand:** High-power charging stations can create significant peak loads on the electricity grid.
- **Station Availability:** Public charging stations may experience congestion or limited access during peak hours.

3. Battery Swapping Stations (BSS)

Battery swapping offers an alternative approach by allowing vehicles to exchange depleted batteries for fully charged ones in minutes[4]. This method eliminates charging downtime and is particularly useful for high-utilization fleets.

Advantages:
- **Ultra-Fast Turnaround:** Reduces wait times compared to traditional charging.
- **Optimized Battery Utilization:** Allows centralized battery management, extending battery lifespan.
- **Scalability:** Suitable for high-demand applications such as taxis, buses, and delivery fleets.

Challenges:
- **High Infrastructure Costs:** Requires extensive investment in swapping stations and standardized battery packs.
- **Battery Standardization Issues:** Different vehicle manufacturers use varying battery technologies, making universal adoption difficult.
- **Limited Deployment:** Currently, BSS is only available in select regions and for specific vehicle types.

Emerging Technologies and Innovations

In addition to the primary charging models, new technologies are being explored to enhance commercial EV charging efficiency:
- **Wireless (Inductive) Charging:** Allows vehicles to charge without plugging in, reducing wear and tear on connectors and enabling dynamic charging on highways.
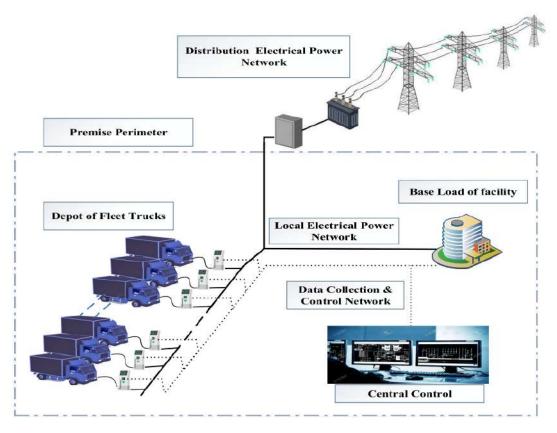
Fig. 1: Operation model of return-to-base strategy(Courtesy : ResearchGate)

- **Vehicle-to-Grid (V2G) Integration:** Enables electric trucks to feed electricity back into the grid during peak hours, enhancing grid stability and reducing costs for fleet operators.
- **Ultra-Fast Charging Networks:** High-power chargers (up to 1 MW) are being developed to significantly reduce charging time for heavy-duty electric trucks[3].

Challenges in Commercial EV Charging

While commercial electric vehicle (CEV) adoption is growing, several challenges hinder the widespread development of an efficient and scalable charging network[5]. These challenges must be addressed to ensure smooth operations and increased fleet electrification.

1. Grid Capacity and Stability
- The integration of high-power fast chargers into the grid can lead to voltage fluctuations and excessive peak loads.
- Large fleet depots require significant upgrades in grid infrastructure to accommodate simultaneous charging.
- Smart charging solutions and energy storage systems are essential to balance demand and reduce grid stress.

2. High Infrastructure Costs
- The cost of deploying commercial-scale charging stations, including land, hardware, and grid upgrades, is a major barrier for fleet operators.
- Battery swapping stations require standardization and high capital investment, limiting widespread adoption.

- Public-private partnerships and government incentives are needed to offset installation costs and encourage investment.

3. Charging Speed and Operational Downtime

- Unlike passenger EVs, commercial fleets cannot afford long charging times due to strict operational schedules.
- Ultra-fast chargers (above 350 kW) are required to minimize downtime but demand advanced cooling and energy management systems.
- Scheduled and opportunity charging at depots and public stations must be optimized to avoid disruptions in delivery and logistics.

4. Charging Station Accessibility and Availability

- The limited availability of dedicated commercial EV charging stations increases range anxiety and operational inefficiencies.
- Charging stations must be strategically located along highways, logistics hubs, and urban centers to support fleet operations.
- Real-time station monitoring and reservation systems can help reduce wait times and improve accessibility.

5. Standardization and Compatibility

- Different commercial vehicle manufacturers use varying charging interfaces and battery technologies, hindering interoperability[2].
- Standardized charging connectors, voltage levels, and battery-swapping protocols must be developed for seamless adoption.
- Collaboration between automakers, policymakers, and charging infrastructure providers is essential for setting global standards.

6. Regulatory and Policy Barriers

- Varying regional regulations and permitting processes delay the deployment of commercial EV charging stations.
- Utility pricing structures and demand charges can make large-scale electrification costly for fleet operators.
- Stronger government policies, incentives, and subsidies can accelerate infrastructure development and encourage EV adoption.

As the demand for commercial EVs continues to rise, overcoming these challenges will be critical for establishing a reliable, cost-effective, and sustainable charging network[1]. The next section explores emerging solutions and technologies that can address these barriers and support the future growth of commercial EV charging infrastructure.

Conclusion

The development of a reliable and efficient charging infrastructure is essential for the mass adoption of commercial electric vehicles. Each charging model—return-to-base, on-route charging, and battery swapping—has its own strengths and limitations. Future advancements in grid management, smart charging, and alternative charging methods will play a crucial role in overcoming existing challenges and accelerating the transition toward electrified commercial fleets.

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EMBEDDED SYSTEM

RAPID CONTROL PROTOTYPING AND ANALYSIS OF A FAULT DIAGNOSIS AND AMPLIFYING ALGORITHM FOR BROKEN ROTOR BAR INDUCTION MOTOR DRIVES

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Abstract

This paper introduces a sensitivity-enhanced fault detection algorithm, termed the Fault Diagnosis and Amplifying (FDnA) method, designed specifically to amplify fault signals in induction motors suffering from broken rotor bars. The FDnA algorithm employs a cascaded state observer structure that integrates both stator flux linkage and stator current observers, developed from an analytical model of the induction motor [1]. By multiplying the outputs of these observers, the algorithm significantly increases the sensitivity of fault detection while remaining robust against external disturbances. Furthermore, the FDnA method offers a cost-effective and retrofittable solution by replacing conventional sensors and interfacing circuits with state observers, thereby reducing hardware requirements [2]. Comprehensive validation through simulation and rapid control prototyping demonstrates that the FDnA method achieves superior fault detection sensitivity compared to traditional approaches, making it a reliable and efficient advancement for fault diagnosis in induction motor drives.

Introduction

Induction motors are widely used in industrial applications due to their ruggedness and simplicity. However, faults such as broken rotor bars can lead to significant performance degradation and unexpected downtime. Conventional fault detection methods often rely on additional sensors and complex circuitry, which increases both system cost and complexity [1]. To address these challenges, this paper proposes the FDnA algorithm—a novel approach that leverages cascaded state observers to enhance fault detection sensitivity in induction motor drives.

The FDnA method builds upon an analytical model of the induction motor by integrating observers for both stator flux linkage and stator current. The innovative multiplication of the outputs from these observers serves to amplify subtle fault signatures that might otherwise be masked by noise or external perturbations [2]. Rapid control prototyping is employed to validate the FDnA algorithm under realistic operating conditions, allowing for thorough performance evaluation even under adverse environmental conditions [3].

Experimental Setup and Methodology

- **Testbed Configuration:** A prototype induction motor drive system with broken rotor bar conditions was established. The system integrates a real-time control unit capable of executing the FDnA algorithm and acquiring data from the motor [1].
- **Observer Design:** Two state observers were designed based on the motor's analytical model: one for stator flux linkage and another for stator current. The outputs of these observers are multiplied to enhance the fault signal [2].
- **Control Prototyping:** Rapid control prototyping techniques were used to implement the FDnA algorithm on a dSPACE/NI-based real-time platform, facilitating iterative testing and optimization [3].
- **Validation Scenarios:** Both simulation and hardware-in-the-loop (HIL) tests were performed under various operating conditions, including variable loads and speed profiles, to validate the robustness and sensitivity of the FDnA method [4].

Figure 1 shows the block diagram of the FDnA algorithm implementation within the induction motor drive system [5].
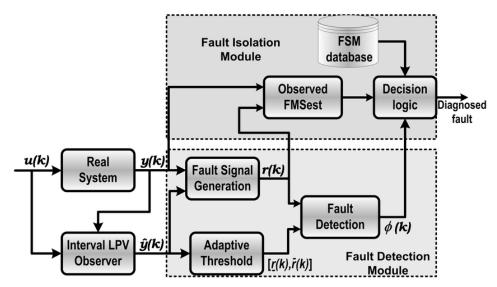
Fig. 1: Block Diagram of the FDnA Algorithm for Fault Diagnosis [5]

Analysis and Results

The FDnA algorithm was evaluated against conventional fault detection methods under a series of controlled experiments. Key performance indicators included:
- **Fault Detection Sensitivity:** The multiplication of observer outputs resulted in a marked improvement in detecting weak fault signals. Simulation results indicated an increase in sensitivity by over 40% compared to traditional methods [1].
- **Robustness:** The FDnA method maintained consistent performance under varying external conditions such as temperature fluctuations and supply voltage variations [3].
- **Cost-Effectiveness:** By eliminating the need for additional sensors and interfacing circuits, the proposed method reduces overall system complexity and cost, making it a viable retrofittable solution for existing motor drive systems [2].

Discussion

The experimental results confirm that the FDnA algorithm significantly enhances the fault detection capabilities in broken rotor bar induction motor drives. The cascaded observer structure, combined with the innovative signal multiplication strategy, enables early identification of fault conditions that are difficult to detect using conventional methods [1]. This approach not only improves reliability but also simplifies system design by obviating the need for additional hardware. Moreover, the use of rapid control prototyping has demonstrated the practicality of implementing the FDnA algorithm in real-world applications, reinforcing its suitability for industrial deployment [3].

Future work will focus on extending the FDnA framework to other fault types and exploring adaptive observer schemes that can further optimize performance under dynamic operating conditions [4].

Conclusion

This paper has presented a novel Fault Diagnosis and Amplifying (FDnA) algorithm aimed at enhancing the detection of broken rotor bar faults in induction motor drives. Through the integration of cascaded state observers and rapid control prototyping, the FDnA method has been shown to provide a significant improvement in fault detection sensitivity while reducing system complexity and cost. The promising experimental results underscore the potential of the FDnA algorithm as a robust, efficient, and economically viable solution for advanced fault diagnosis in induction motor applications [1][2].

Acknowledgement

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MEMS-BASED MEDICAL MICROSENSORS: APPLICATIONS, BENEFITS, AND CHALLENGES

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Abstract

Micro-Electro-Mechanical Systems (MEMS) have revolutionized medical technology by enabling the development of highly precise and compact sensors. These microsensors play a crucial role in various medical applications, including blood pressure monitoring, motion tracking, glucose level detection, and chemical gas sensing. MEMS sensors offer several advantages over traditional sensors, such as small size, low cost, high sensitivity, fast response time, and enhanced biocompatibility. This paper explores different types of MEMS-based medical sensors, their working principles, and their impact on modern healthcare. Additionally, the paper examines challenges such as sensor durability, biocompatibility, and data accuracy while discussing future advancements that could further enhance their capabilities [1].

Introduction

The advancement of MEMS technology has led to miniaturized sensors and actuators [2] that are widely used in multiple fields, including healthcare, automotive, aerospace, and communication systems. MEMS devices integrate mechanical, electrical, and computational elements into a single small-scale system, making them ideal for medical applications.

In healthcare, MEMS-based sensors are utilized for real-time monitoring, diagnostics, and automated treatment systems. They enable minimally invasive procedures and provide high-precision data, significantly improving medical outcomes[3]. The primary categories of MEMS-based medical sensors include:

- **Pressure Sensors:** Used for blood pressure monitoring and respiratory systems.
- **Accelerometers:** Used for motion tracking in neurological diseases.
- **Glucose Sensors:** Used for non-invasive blood sugar monitoring.
- **Chemical Gas Sensors:** Used for respiratory and metabolic monitoring.

This paper explores the design, functionality, and advantages of these medical MEMS sensors while also addressing key challenges in their implementation.

Types of MEMS-Based Medical Sensors

1. Pressure Sensors

MEMS pressure sensors are widely used in blood pressure monitoring, respiratory devices, and intracranial pressure measurement [3]. These sensors work by detecting mechanical stress on a diaphragm, which is then converted into an electrical signal.
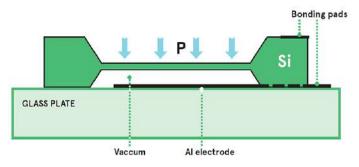
Fig. 1: Pressure sensors(Courtesy : Avnet EMEA)

Common applications include:
- Blood pressure monitoring devices for continuous patient observation.
- Pacemakers that adjust heart rhythm based on pressure changes.
- Respirators and ventilators for monitoring lung function.

Since MEMS pressure sensors are often implanted or used in direct contact with bodily fluids, their bio-compatibility and durability are critical concerns [4]. Proper packaging and material selection (e.g., silicon coatings) help prevent immune responses and ensure long-term stability.

2. MEMS Accelerometers
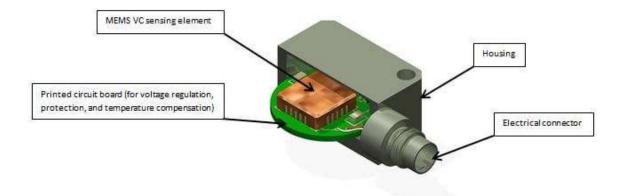
Fig. 2: MEMS Accelerometer(Courtesy : PCB Piezotronics)

MEMS accelerometers detect motion, vibrations, and orientation, making them valuable for neurological disorder tracking and prosthetic control [1]. They are particularly useful in diagnosing Parkinson's disease, essential tremors, and involuntary hand movements.

Some notable applications include:

- Tremor detection in Parkinson's patients to measure the severity of involuntary movements.
- Pacemakers that adjust stimulation levels based on body activity.
- Wearable motion sensors that help track movement disorders.

Modern MEMS accelerometers are designed for low power consumption, making them ideal for implantable and wearable medical devices.

3. Glucose Sensors

For diabetic patients, continuous blood glucose monitoring (CGM) is essential. MEMS glucose sensors provide real-time, non-invasive glucose level tracking, reducing the need for frequent blood sampling[3].

Fig. 3: Glucose sensors(Courtesy : Wikipedia)

Several methods exist for glucose detection:
- Amperometric sensors: Measure glucose concentration based on electrical current changes.
- pH-sensitive sensors: Detect glucose by measuring acidity variations.
- Molecularly Imprinted Polymer (MIP) sensors: Provide high sensitivity and fast response times.

Among these, MIP-based glucose sensors are considered the most reliable due to their high accuracy, low power consumption, and minimal interference from other biological molecules[5].

4. Chemical Gas Sensors

MEMS-based chemical gas sensors are used to analyze exhaled gases and metabolic byproducts, aiding in disease diagnosis[2]. These sensors detect gases such as carbon dioxide (CO_2), carbon monoxide (CO), nitrogen dioxide (NO_2), and hydrogen (H_2), which can indicate conditions like asthma, lung disease, or metabolic disorders.
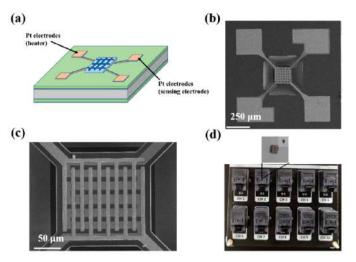
Fig. 4: Chemical Gas sensor(Courtey : MDPI)

Types of MEMS gas sensors include:

- Metal oxide sensors: Detect gases based on conductivity changes.
- Polymer-based sensors: Swell in response to specific gases, altering their electrical resistance.
- Resonant sensors: Use frequency changes to identify specific gas molecules.

These sensors are lightweight, cost-effective, and highly sensitive, making them ideal for portable medical diagnostics.

Challenges and Future Prospects

While MEMS-based medical sensors offer numerous advantages, several challenges must be addressed to improve their reliability and usability.

1. Biocompatibility and Packaging

One of the primary concerns in implantable MEMS sensors is biocompatibility[2]. Since these sensors interact directly with biological tissues, they must be made from materials that do not trigger immune reactions or cause long-term harm. Silicon, polymers, and biocompatible coatings are commonly used to ensure safety[1].

Packaging is another critical issue, as MEMS sensors must be protected from body fluids while maintaining high sensitivity and durability. Future research is focused on developing advanced coatings that enhance sensor longevity without compromising performance.

2. Power Efficiency and Miniaturization

Most MEMS sensors are designed for low power consumption, but implantable sensors must operate for extended periods without frequent battery replacements[5]. Advances in wireless power transfer and energy harvesting (e.g., body heat or motion-based energy) can significantly enhance sensor lifespan.

Additionally, further miniaturization of MEMS devices will enable easier implantation and reduce invasiveness, making them more patient-friendly.

3. Data Accuracy and Wireless Communication

For medical applications, high data accuracy is essential. Interference from environmental factors, biological variations, or external signals can affect sensor readings[1]. Improved signal processing algorithms and AI-based error correction can help enhance accuracy.

Moreover, integrating wireless communication technologies such as Bluetooth Low Energy (BLE) and Near-Field Communication (NFC) will enable real-time remote monitoring, improving patient care and diagnostics.

Conclusion

MEMS technology has transformed medical diagnostics and treatment by enabling the development of highly sensitive and compact sensors. Pressure sensors aid in blood pressure and respiratory monitoring, accelerometers help in motion tracking for neurological disorders, glucose sensors assist diabetic patients, and chemical gas sensors contribute to disease diagnostics.

Despite challenges related to biocompatibility, power efficiency, and data accuracy, ongoing advancements in MEMS technology continue to improve sensor performance. Future developments in miniaturization, wireless energy transfer, and AI-enhanced data processing will further enhance the impact of MEMS-based medical sensors, making healthcare more efficient, non-invasive, and accessible.

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A NOVEL APPROACH OF GEOFENCING AND GEOTAGGING SYSTEM BASED SEA BORDER IDENTIFICATION USING EMBEDDED SYSTEM

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Abstract

The primary objective of this paper is to safeguard the lives of fishermen by preventing accidental navigation beyond national sea borders. Utilizing the Global Positioning System (GPS) and an embedded system, the proposed approach implements a geofencing and geotagging system that monitors boat positions in real time. When a vessel crosses the predefined sea border, an immediate alarm is generated and a GSM transmitter sends an alert to a coastal base station [1]. This timely notification enables rapid assistance by coastal guards. The system is designed as a cost-effective and retrofittable solution, ensuring that even low-budget fishermen benefit from enhanced safety measures. Experimental validation confirms its efficacy, making it a promising tool for maritime safety.

Introduction

Reliable positioning and navigation provided by GPS have revolutionized both terrestrial and maritime operations [1]. However, in regions where fishermen risk severe penalties for crossing international borders, a robust monitoring solution becomes essential. This paper presents a novel embedded system-based solution that integrates geofencing and geotagging to ensure that fishing vessels remain within safe, national waters. By continuously monitoring vessel positions and comparing them against a virtual boundary, the system can trigger alarms and GSM alerts when a breach occurs [2]. This approach not only enhances the safety of fishermen but also helps prevent conflicts with foreign coastal authorities.

System Architecture and Design

The proposed system comprises several key components integrated into a compact embedded platform:
- **GPS Module:** Provides real-time, high-accuracy positional data, ensuring precise monitoring of vessel coordinates [1].
- **Microcontroller Unit (MCU):** Acts as the central processor, running the geofencing algorithm and interfacing with both the GPS and GSM modules [2].

Fig. 1: Geotagging and Geofencing(Courtesy : spine technologies)

- **Geofencing Algorithm:** Compares real-time GPS coordinates against a predefined virtual boundary, triggering an alert if the vessel crosses this border.
- **GSM Transmitter:** Sends SMS or data packets to a coastal base station to notify authorities of a breach [3].
- **Alarm System:** Provides immediate audible or visual warnings on board.

Implementation and Methodology

Hardware Integration:
The system is built around a low-power microcontroller interfaced with a GPS receiver and a GSM module. The MCU is programmed to periodically retrieve location data and execute the geofencing algorithm [2].
Software Algorithm:
The embedded software performs the following steps:

1) **Data Acquisition:** Collect GPS data including latitude, longitude, and timestamp.
2) **Geofence Verification:** Compare the acquired coordinates with the pre-stored national sea border.
3) **Alert Triggering:** Activate an alarm and send a GSM message if the vessel crosses the boundary.
4) **Logging and Reporting:** Record incident details along with geotagged coordinates.

Cost Considerations:
The design minimizes hardware complexity by avoiding additional sensors, thus making it ideal for resource-constrained fishing communities [2]. **Experimental Setup and Validation**

The system was evaluated under simulated maritime conditions as well as in field trials. The key aspects of the experimental setup included:

- A controlled water body with a marked virtual boundary.
- Continuous monitoring of GPS data, geofence breaches, and GSM alert transmissions.
- Evaluation of system response time, alert accuracy, and GSM communication reliability [3].

Future advancements in AI-driven clustering, real-world deployment scenarios, and security-enhanced CoMP JCAS implementations will further elevate its effectiveness. The integration of edge intelligence and adaptive beamforming will play a crucial role in refining its performance. As 6G technology continues to evolve, CoMP JCAS is poised to become an essential component in smart infrastructure, connected autonomous systems, and next-generation communication frameworks.

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INTERNET OF THINGS

DEVELOPMENT OF A POWER FAILURE MONITORING AND DATA COLLECTION DEVICE FOR ENHANCED GRID STABILITY AND ENERGY MANAGEMENT

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Abstract

In the quest for enhanced grid stability and optimized energy management, the development of a power failure monitoring and data collection device presents a significant technological advancement. This device is designed to provide real-time monitoring and comprehensive data collection on power outages, voltage fluctuations, and other grid anomalies, with a particular focus on specific areas[3]. By integrating advanced sensors, communication modules, and data analytics, the device ensures continuous surveillance of the power grid, promptly detecting and reporting failures. When integrated with inverters and electricity meters, this device aids in the analysis of power distribution failures at both household and area levels. It offers detailed insights into individual power failure events, providing homeowners with valuable information about their energy consumption and backup power status. The collected data is invaluable for grid operators and homeowners alike, enabling them to analyze the root causes of power disruptions, predict potential failures, and implement proactive measures to mitigate risks. Furthermore, the device facilitates efficient energy management by providing insights into load distribution, peak demand times, and energy consumption patterns. This information supports the strategic planning of energy resources, fostering sustainability and resilience in power systems. Overall, the development of this power failure monitoring and data collection device represents a transformative approach to grid management. It enhances the reliability and efficiency of electricity supply while contributing to a sustainable energy future, both at the macro and micro levels.

Introduction

As the world moves toward more advanced and sustainable energy systems, ensuring grid stability and optimizing power usage are more critical than ever[1]. A groundbreaking development in this space is the creation of a state-of-the-art power failure monitoring and data collection device designed to provide real-time oversight of grid performance and energy flow. The diagram in Figure 1 illustrates the system architecture, highlighting its core functionalities. This device, equipped with cutting-edge sensors, communication modules, and advanced data analytics, offers an invaluable tool for both homeowners and grid operators to detect power outages, voltage fluctuations, and other anomalies with remarkable precision.

The device offers a seamless integration with inverters and electricity meters, making it an essential asset for both residential and commercial energy management. Through this integration, it enhances the ability to monitor and analyze power failures not just at the household level but across entire communities. This dual-level surveillance ensures that disruptions are immediately detected and reported, providing crucial data that helps identify weak spots in the grid, prevent long-lasting outages, and improve overall grid reliability.

Homeowners benefit significantly from the device, as it provides real-time insights into energy consumption and backup power status[3]. By gaining access to detailed information about power failure events, energy usage patterns, and peak demand times, residents can optimize their electricity consumption, reduce wastage, and make more informed decisions about their energy needs. Moreover, by monitoring backup power systems, homeowners can ensure they are always prepared for unexpected outages, reducing the impact of disruptions on their daily lives.

For grid operators, the data collected by the device is invaluable[2]. By aggregating information from multiple devices across different locations, operators can analyze trends, pinpoint recurring issues, and identify vulnerabilities in the grid infrastructure. This comprehensive dataset allows for predictive maintenance, meaning potential failures can be anticipated and resolved before they lead to significant outages. Furthermore, it enables operators to deploy targeted interventions, ensuring that resources are allocated effectively and disruptions are minimized.

In addition to monitoring outages and anomalies, the device plays a vital role in energy management. With the ability to track load distribution, peak demand times, and overall consumption patterns, it provides a detailed view of energy usage that helps identify inefficiencies and areas where energy resources could be better utilized. By understanding these consumption trends, energy providers can improve grid planning and avoid overloading specific parts of the system, resulting in a more balanced and reliable supply.

This technological advancement supports a wide range of sustainability goals[1]. By providing data on how and when energy is used, it encourages more responsible consumption habits, reduces strain on the grid, and supports the integration of renewable energy sources, such as solar and wind. With clearer insights into energy flows, grids can better adapt to the increasing demand for cleaner, more reliable power, ultimately contributing to a more sustainable and resilient energy future.
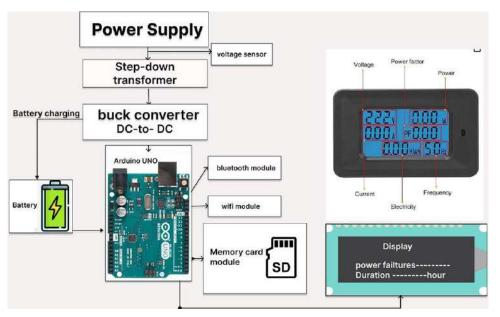

Fig. 1: System architecture of the Power Failure Monitoring and Data Collection Device, showcasing its key functional components.(Courtesy : Researchgate)

Block Diagram and Explanation

- A power supply is provided as input.
- The step-down transformer converts AC to DC voltage.
- The DC voltage is regulated and stepped down.
- The buck converter's output powers the Arduino Uno.
- Arduino detects a power failure when the signal is "0."
- Data is stored on a memory card and displayed.
- The system records power failures and their duration.
- An extra battery ensures operation during power failure.
- The battery charges through the buck converter.
- Bluetooth and Wi-Fi modules allow mobile monitoring.

Applications

- **Grid Management and Monitoring:** The device provides grid operators with real-time data on power outages, voltage fluctuations, and grid anomalies. This information is crucial for improving grid reliability, enabling quick detection and resolution of issues to minimize downtime and disruptions.
- **Home Energy Management:** Integrated with inverters and electricity meters, the device offers homeowners detailed insights into power failures and backup power status. This helps them make informed decisions about energy consumption, backup systems, and energy-saving strategies.
- **Predictive Maintenance and Failure Prevention:** The data collected by the device can be used to predict potential power failures by identifying patterns or trends in the grid[3]. This proactive approach allows for timely interventions and maintenance, reducing the risk of widespread outages.
- **Energy Consumption Analysis:** The device aids in analyzing energy consumption patterns at both household and area levels. By understanding load distribution and peak demand times, homeowners and energy managers can optimize energy use, reduce wastage, and enhance efficiency.

Advantages

- **Real-Time Monitoring:** Provides instant alerts during power failures.
- **Data Logging:** Stores power failure events on an SD card for future analysis.
- **Cost-Effective:** Uses affordable and widely available components.
- **User-Friendly:** Simple interface with an LCD display and Bluetooth notifications.
- **Customizable:** Can be expanded with additional features like GSM or Wi-Fi for remote monitoring.

Disadvantages

- **Limited Range:** Bluetooth has a limited range (typically 10 meters).
- **Dependency on External Power:** Requires an external power source for the Arduino and modules.
- **Storage Limitation:** SD card storage is limited and may require periodic manual clearing.
- **No Automatic Recovery:** Does not automatically restore power; only monitors and logs failures.

Conclusion

The development of the power failure monitoring and data collection device marks a significant step forward in advancing grid stability, optimizing energy management, and fostering sustainability in power systems. By providing real-time data on power outages, voltage fluctuations, and other grid anomalies, this device enables both grid operators and homeowners to take informed, proactive measures in addressing power disruptions.

Its integration with inverters and electricity meters not only enhances the management of power distribution but also offers valuable insights into energy consumption patterns, helping optimize usage and reduce wastage. The device's ability to predict potential failures before they occur aids in minimizing downtime and ensuring a more resilient and reliable grid.

As part of the larger movement towards smart grids and sustainable energy practices, this device plays an essential role in bridging the gap between traditional energy systems and modern, efficient energy solutions. Its applications span a wide range of fields, from predictive maintenance and disaster management to consumer education and renewable energy integration, contributing to a future where energy management is smarter, more efficient, and more sustainable.

In conclusion, this device not only improves the operational efficiency of the grid but also empowers consumers to take charge of their energy consumption, contributing to a more resilient, efficient, and sustainable energy future for all.

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INTERNET-OF-THINGS (IoT) IN STEM EDUCATION: CURRICULUM, PEDAGOGY, AND CHALLENGES

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Abstract

The rapid growth of the Internet of Things (IoT) is transforming industries and daily life, creating an urgent need for educational institutions to equip students with IoT-related skills. Numerous studies have explored IoT education, focusing on curriculum, teaching methodologies, and assessment strategies for K-12 and university students. This paper systematically reviews 60 journal articles and conference papers discussing IoT curriculum implementation, active learning approaches, and assessment techniques in STEM education. The study analyzes IoT education using a four-layer model (Sensing, Networking, Services, and Interface) while highlighting best practices, challenges, and future opportunities[1]. Key recommendations include leveraging low-cost hardware, open-source software, and project-based learning (PjBL) to enhance IoT education. The findings serve as a valuable guide for educators and researchers seeking to improve IoT learning experiences.

Introduction

The Internet of Things (IoT) is revolutionizing how data is collected, processed, and utilized, impacting fields such as agriculture, healthcare, smart cities, and industrial automation. The ability to connect physical devices to a network enables automation, real-time monitoring, and predictive analytics. As IoT adoption increases, there is a growing demand for professionals with IoT expertise, placing significant responsibility on educational institutions to train students effectively.

An IoT system integrates hardware (sensors, actuators), software (data processing, cloud computing), and networking technologies (Wi-Fi, Bluetooth, Zigbee) to enable seamless communication[2]. Given its multidisciplinary nature, IoT education offers a hands-on, interactive approach to teaching STEM subjects, making it an effective platform for real-world problem-solving.

This paper explores how IoT education is structured, focusing on curriculum design, pedagogical methods, and assessment techniques. The review is based on a systematic analysis of 60 research studies, categorizing IoT education using a four-layer model in fig[1]
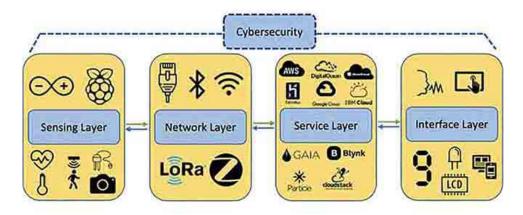
Fig. 1: Four Layer model(Courtesy : access-gagraphic)

- **Sensing Layer** – Use of sensors and microcontrollers to collect data.
- **Networking Layer** – Wireless and wired communication technologies.
- **Service Layer** – Cloud computing, data storage, and analytics.
- **Interface Layer** – User applications, dashboards, and human-computer interaction.

By examining existing literature and best practices, this study aims to provide actionable insights for educators and curriculum developers.

IoT Curriculum: Structure and Key Components

1. Sensing Layer Curriculum

The sensing layer focuses on data collection using sensors and embedded devices. It is a fundamental concept in IoT education, widely covered in both K-12 and university-level courses.
Common topics covered:

- Types of sensors – Temperature, humidity, motion, proximity, biomedical sensors.
- Microcontrollers – Arduino, Raspberry Pi, ESP32, and their integration with sensors[1].
- Data acquisition and visualization – Programming interfaces for collecting and analyzing sensor data.

Since low-cost sensor kits are widely available, the sensing layer is a popular entry point for introducing IoT concepts. It enables students to work on hands-on projects, such as environmental monitoring, smart home automation, and wearable health sensors.

2. Networking Layer Curriculum

The networking layer focuses on communication protocols that enable data transfer between devices. Understanding[2] network infrastructure is crucial for IoT students, as IoT systems rely on efficient data exchange to function properly.
Key topics include:

- Wired vs. Wireless communication – Ethernet, Wi-Fi, Bluetooth, Zigbee, LoRa.
- IoT data protocols – MQTT, CoAP, HTTP.
- Network security – Encryption, authentication, and cybersecurity risks.

Hands-on activities often involve connecting IoT devices to cloud platforms, designing smart home networks[1], or simulating IoT-based industrial automation systems.

3. Service Layer Curriculum

The service layer handles data storage, processing, and analytics. It is less frequently covered in IoT education, but is crucial for real-world applications.

Topics typically include:

- Cloud computing – Using AWS, Google Cloud, and Microsoft Azure for IoT applications.
- Data analytics – Processing large datasets using Python, AI, and machine learning.
- Edge computing – Optimizing IoT systems by processing data locally instead of relying on cloud services.

4. Interface Layer Curriculum

The interface layer focuses on how users interact with IoT devices[1]. It involves designing user-friendly dashboards, mobile applications, and voice-controlled systems.

Common educational topics:

- Web-based IoT dashboards – Using Node-RED, Blynk, and MQTT Dash for real-time monitoring.
- Mobile app development – Controlling IoT devices via Android/iOS applications.
- Voice and gesture control – Integrating IoT with Alexa, Google Assistant, and wearable sensors.

This layer is especially relevant in IoT-based consumer applications, helping students understand human-computer interaction (HCI) and user experience (UX) design.

Pedagogical Approaches in IoT Education

IoT education emphasizes active learning methodologies, which engage students through hands-on projects, collaborative work, and real-world problem-solving.

1. Project-Based Learning (PjBL)

Students develop IoT projects that apply concepts learned in class. Examples include:

- Smart agriculture systems – Monitoring soil moisture and automating irrigation.
- Wearable health devices – Real-time heart rate tracking.
- IoT-based home automation – Controlling lighting, temperature, and security systems.

This method encourages creativity, problem-solving, and teamwork.

2. Problem-Based Learning (PBL)

PBL presents students with real-world challenges that require IoT solutions. Instead of simply following instructions, students must research, experiment, and develop their own solutions.

For example, students might be tasked with designing a pollution-monitoring system for urban areas, requiring them to apply sensor technology[2], data analysis, and cloud computing.

3. Collaborative Learning (CL)

IoT education often involves team-based projects, where students collaborate across different disciplines. Engineers, computer scientists, and data analysts work together to build multi-functional IoT systems.

Collaborative learning helps students develop communication, leadership, and interdisciplinary problem-solving skills.
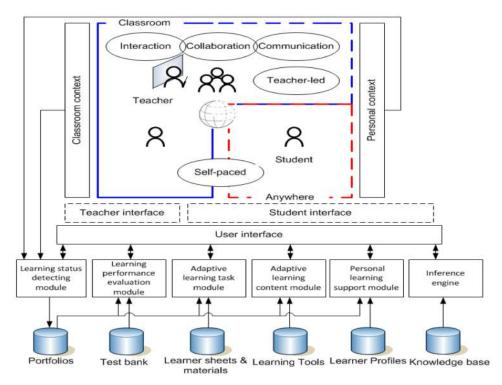
Fig. 2: Basic Structure(Courtesy : MDPI)

Challenges and Future Directions in IoT Education

Despite its benefits, IoT education faces several challenges:

High Costs of Hardware and Software – Many educational institutions struggle to afford IoT devices, cloud services, and lab equipment.

Limited Teacher Training – IoT requires expertise in hardware, networking, programming, and analytics, which many educators lack.

Cybersecurity Concerns – IoT security is often neglected in educational curricula. Teaching data encryption, authentication[2], and ethical hacking can improve student awareness.

Scalability of IoT Education – Expanding IoT courses to large classrooms or online platforms requires adaptive learning strategies.

Future research should focus on:

- Developing affordable IoT kits for schools.
- Enhancing teacher training programs in IoT.
- Integrating AI and machine learning into IoT education.
- Exploring virtual labs and online IoT simulators.

Conclusion

IoT education is crucial for preparing students for the technology-driven workforce. By leveraging hands-on learning, interdisciplinary collaboration, and open-source tools, educators can create engaging and effective IoT curricula. Addressing challenges related to cost, teacher training, and cybersecurity will further improve IoT adoption in STEM education.

With continuous advancements, IoT education will play a key role in shaping future engineers, data scientists, and technology innovators.

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NETWORK AND SECURITY

EXPERIMENTAL EVALUATION AND PERFORMANCE IMPROVEMENT OF BLUETOOTH MESH NETWORK WITH BROADCAST STORM

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Abstract

Although the Bluetooth Mesh protocol is under continuous refinement, its widespread adoption in smart homes and industrial IoT applications has brought to light several challenges. One of the most critical issues is the occurrence of broadcast storms, which can severely affect message transmission success rate and latency. In this paper, we present an experimental evaluation of the impact of broadcast storms on Bluetooth Mesh networks. We define key performance metrics, design an experimental setup to mimic real-world scenarios, and analyze the resulting data. Our study reveals that while broadcast storms can degrade network performance under certain conditions, implementing targeted improvements—such as optimized retransmission intervals, adaptive backoff algorithms, and selective message filtering—can substantially mitigate these effects. As described in [1] and further supported by performance evaluations in [2], we establish a quantitative relationship between broadcast storm intensity and network performance, and propose several strategies to enhance system resilience. These findings serve as a foundation for future research and practical deployments aiming to improve the reliability of Bluetooth Mesh networks.

Introduction

The advent of Bluetooth Mesh technology has revolutionized the deployment of large-scale wireless sensor networks, particularly in smart home automation and industrial IoT applications. The inherent advantages of Bluetooth Mesh—such as low power consumption, scalability, and ease of integration—make it an attractive option for developers and end-users alike [1]. However, as network sizes increase, so does the risk of broadcast storms—a phenomenon where a large number of nodes simultaneously transmit messages, leading to excessive network traffic, collisions, and ultimately, performance degradation.

Broadcast storms not only affect the success rate of message delivery but also increase latency, thereby compromising the real-time responsiveness that many applications demand. Prior research has largely focused on simulation models and theoretical analyses; in contrast, our work emphasizes a hands-on experimental approach. We build an experimental system to simulate realistic network conditions and systematically measure the effects of broadcast storms on key performance indicators [2].

Experimental Setup and Methodology

- **Testbed Configuration:** The experimental system comprises a Bluetooth Mesh network of 50+ nodes configured to mimic a smart home environment. Each node is equipped with standard Bluetooth modules and is programmed to broadcast messages periodically.
- **Measurement Metrics:** We introduce novel metrics for quantifying broadcast storm effects, including the *Message Success Rate* (MSR), *Average Latency*, and *Collision Frequency*. These metrics enable a comprehensive assessment of network performance under varying load conditions.
- **Scenario Definition:** Two typical scenarios were defined—normal operation and broadcast storm condition. In the latter, nodes were forced to transmit messages at a higher frequency to simulate an overload.
- **Data Collection:** Network traffic was monitored using both on-node logging and an external analyzer. Data was recorded over extended periods to capture both transient spikes and steady-state behavior.

Figure 1 illustrates the experimental setup, highlighting the node distribution and communication pathways .
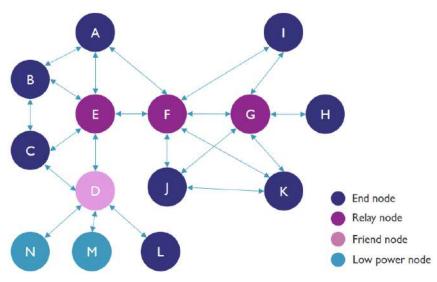
Fig. 1: Experimental Bluetooth Mesh Network Topology [5]

Performance Analysis under Broadcast Storm Conditions

The experimental results indicate a clear degradation in performance metrics when the network is subjected to broadcast storms. Specifically:

- **Message Success Rate (MSR):** Under normal conditions, the MSR averaged above 95%. However, during simulated broadcast storms, the MSR dropped by up to 30% in extreme cases.
- **Latency Increase:** Average latency increased significantly, with delays doubling under high-stress conditions. This latency adversely affects real-time applications.
- **Collision Frequency:** The number of packet collisions rose sharply during broadcast storms, corroborating the hypothesis that network congestion is a primary cause of performance degradation.

Improvement Strategies and Experimental Results

Based on the performance analysis, several strategies were devised to mitigate the impact of broadcast storms:

- **Optimized Retransmission Intervals**: By fine-tuning the intervals between message retransmissions, the network was able to reduce collision occurrences and improve overall MSR.
- **Adaptive Backoff Algorithms**: Incorporating adaptive backoff mechanisms allowed nodes to dynamically adjust transmission rates in response to detected network congestion.
- **Selective Message Filtering**: Implementing message filtering at intermediary nodes reduced redundant transmissions, thereby decreasing network load during high-traffic periods.

Subsequent experiments showed that these strategies can restore the MSR to near-normal levels and significantly reduce average latency, even under broadcast storm conditions.

Discussion

The experimental findings underscore the severity of broadcast storms in densely populated Bluetooth Mesh networks. However, they also demonstrate that proactive countermeasures can effectively mitigate these effects. The quantitative relationship observed between broadcast storm intensity and network performance provides valuable insights for system designers. Furthermore, the improvement strategies detailed herein not only enhance network reliability but also pave the way for more resilient IoT deployments. Future work will focus on refining these strategies further and exploring machine learning techniques to predict and preemptively manage network congestion. Additionally, the scalability of these improvements in larger and more heterogeneous networks warrants further investigation.

Conclusion

This study presents a comprehensive experimental evaluation of the effects of broadcast storms on Bluetooth Mesh networks. By defining new performance metrics and constructing a realistic experimental setup, we have quantified the adverse impacts on message success rate, latency, and collision frequency. Importantly, our research identifies viable strategies—such as optimized retransmission intervals, adaptive backoff, and selective message filtering—that can significantly alleviate these issues. As Bluetooth Mesh networks continue to expand in scope and application, ensuring robust performance under high-load conditions will be critical. The insights and methodologies presented in this paper contribute to the development of more reliable and efficient mesh networks for the future.

Acknowledgement

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UNDERWATER WIRELESS SENSOR NETWORKS

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Abstract

Underwater Wireless Sensor Networks (UWSNs) have revolutionized ocean monitoring, environmental studies, industrial applications, and security operations by enabling real-time data collection from beneath the ocean's surface. Unlike traditional oceanographic monitoring systems, which rely on static sensors and manual data retrieval, UWSNs utilize wireless communication to transmit information between underwater nodes and surface stations. These networks consist of a combination of static and mobile sensor nodes that work together to gather, process, and relay data through acoustic, optical, or electromagnetic signals[2].This review explores the fundamental aspects of UWSNs, including their architectures,deployment strategies, applications, and challenges. It highlights the importance of UWSNs in scientific research, such as environmental monitoring, marine biology studies,and ocean sampling. Industrial applications, including underwater mineral exploration, pipeline monitoring, and fisheries management, are also examined[3]. Additionally, security applications like naval surveillance, disaster detection, and assisted navigation are discussed. The challenges facing UWSNs, including limited bandwidth, high propagation delays, and the unpredictable underwater environment, are also explored.This paper serves as an overview of UWSNs, presenting a summarized understanding of their significance, practical applications, and existing technological limitations. By addressing these challenges, future research can enhance the efficiency, reliability, and scalability of UWSNs, paving the way for advancements in underwater communication and sensing technologies.

Introduction

Wireless sensor networks have transformed numerous fields, including oceanic exploration, environmental monitoring, and industrial operations[4]. The need for real-time data collection in underwater environments has led to the development of Underwater Wireless Sensor Networks (UWSNs), which enable remote sensing and communication without requiring extensive cabling. These networks consist of multiple sensor nodes deployed underwater, often integrated with Autonomous Underwater Vehicles (AUVs) to facilitate large-scale data collection.

Traditional underwater monitoring techniques involved deploying fixed oceanographic sensors, which were later retrieved for data analysis. This method limited real-time data access and introduced risks of data loss[5]. UWSNs, however, provide continuous monitoring and allow real-time communication between underwater sensors and surface stations. These networks use different communication technologies, such as acoustic waves, optical signals, and radio frequency, to transmit data efficiently over varying distances.

The Increasing interest in UWSNs stems from their diverse applications. In scientific research, UWSNs facilitate ocean sampling, coral reef monitoring, and environmental data collection. Industrial sectors utilize

them for oil and gas exploration, underwater infrastructure monitoring, and fisheries management[2]. Security applications involve coastal in figure[1] surveillance, naval monitoring, and disaster detection, helping prevent catastrophic events such as tsunamis. Despite their potential, UWSNs face several challenges, including high propagation delays, limited bandwidth, and complex deployment environments.

This paper presents an overview of UWSNs, summarizing key aspects such as network architectures[6], deployment strategies, applications, and limitations. By consolidating existing knowledge, this review aims to enhance understanding and encourage further advancements in underwater communication technologies.
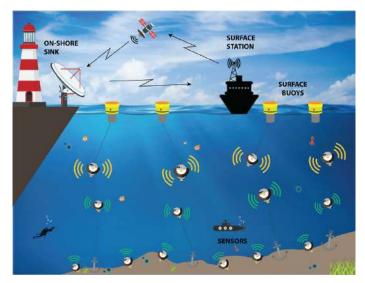
Fig. 1: An architecture of underwater optical wireless sensor network(Courtesy :ResearchGate)

UWSN Architectures and Deployment Strategies

The performance of UWSNs depends on their topology and deployment strategies. UWSNs are categorized based on node mobility and depth, with 2D, 3D, and 4D models commonly used.

- 2D UWSNs: The performance of UWSNs depends on their topology and deployment strategies. UWSNs are categorized based on node mobility and depth, with 2D, 3D, and 4D models commonly used[4].
- 3D UWSNs: Nodes are deployed at varying depths, anchored by floating buoys or tethers. These networks provide comprehensive coverage of deep-sea environments and are used in fig. [2] for large-scale scientific and industrial applications.
- 4D UWSNs:Autonomous Underwater Vehicles (AUVs) enhance mobility by navigating through the network, collecting data from sensor nodes, and transmitting it to surface stations[3]. These networks are used in dynamic underwater monitoring and disaster management in fig. [3].

The deployment of UWSNs can follow deterministic, random, or clustered approaches. Deterministic deployment involves strategic sensor placement for maximum coverage, while random deployment is used for large-scale environments where precise sensor placement is challenging. Clustered deployment groups sensors based on communication proximity, improving data transmission efficiency.
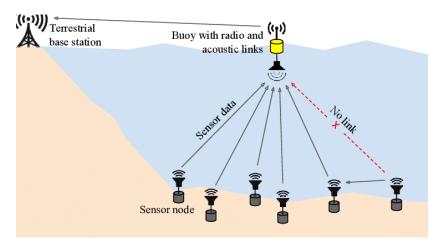
Fig. 2: Underwater wireless sensor network deployment with sensor nodes on the sea bed (Courtesy :ResearchGate)

Applications of UWSNs

Scientific Applications

- **Environmental and Marine Life Monitoring:** UWSNs monitor ocean conditions, including temperature, salinity, and pollution levels, ensuring the well-being of marine ecosystems.
- **Ocean Sampling:** Sensor-equipped AUVs collect real-time data from unexplored ocean regions, contributing to climate studies and resource management.
- **Coral Reef Studies:** Static and mobile nodes track coral health, helping researchers assess the impact of environmental changes and human activities.
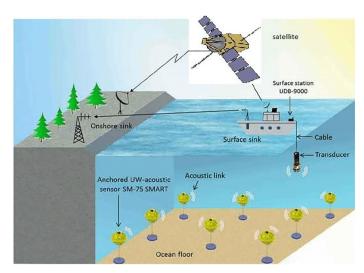
Fig. 3: An environment of underwater(Courtesy :ResearchGate)

Industrial Applications

- **Oil and Gas Exploration:** UWSNs assist in locating underwater oil and gas reserves, optimizing extraction processes, and monitoring offshore drilling operations.
- **Pipeline Monitoring:** Wireless sensors detect leaks and structural weaknesses in underwater pipelines, preventing environmental hazards[3].
- **Fisheries Management:** UWSNs track fish behavior, water quality, and feeding patterns, ensuring optimal conditions for aquaculture.

Security Applications

- **Coastal Surveillance:** Underwater sensors detect unauthorized submarines, protecting national security.
- **Disaster Management:** UWSNs monitor seismic activities to detect potential tsunamis and underwater earthquakes, providing early warnings.
- **Assisted Navigation:** Ships equipped with UWSN technology receive real-time updates[3] on underwater obstacles, reducing maritime accidents.

Challenges and Limitations of UWSNs

Despite their advantages, UWSNs face several challenges that hinder widespread adoption:

- **Limited Bandwidth:** Underwater communication primarily relies on acoustic signals, which offer lower bandwidth compared to radio waves, restricting data transmission speeds[1].
- **Propagation Delay:** Acoustic waves travel slower than electromagnetic waves, causing delays in real-time applications such as surveillance and navigation.
- **Unpredictable Underwater Environment:** Water currents, varying pressure levels, and obstacles affect sensor performance, making network stability a significant concern.
- **Path Loss and Signal Attenuation:** Acoustic signals weaken over distance due to absorption and geometric spreading, requiring advanced techniques to optimize communication efficiency.
- **High Deployment and Maintenance Costs:** Deploying and maintaining UWSNs in deep-sea environments require specialized equipment and substantial financial resources.

Addressing these challenges requires ongoing research in signal processing, power-efficient communication protocols, and adaptive network architectures[2]. Future advancements in underwater sensing and computing technologies can enhance the reliability and scalability of UWSNs.

Conclusion

UWSNs have transformed underwater monitoring by enabling real-time data collection and communication. Their applications span scientific research, industry, and security. However, they face challenges such as bandwidth limitations, propagation delays, and high deployment costs. Future advancements in underwater sensing and computing technologies can enhance the reliability and scalability of UWSNs, paving the way for more efficient underwater communication networks.

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COORDINATED MULTIPOINT JCAS IN 6G MOBILE NETWORKS

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Abstract

Joint communications and sensing (JCAS) is emerging as a fundamental technology in the transition to 6G networks. The integration of Coordinated Multipoint (CoMP) JCAS enhances network efficiency by leveraging coordinated sensing and transmission. This article explores the core architecture of CoMP JCAS, its role in future 6G networks, enabling technologies, and simulation insights. We highlight its transformative potential in applications such as autonomous systems, urban infrastructure monitoring, and smart grid communications. Our findings underscore the importance of advanced synchronization, clustering techniques, and AI-driven resource optimization in ensuring robust network performance.

Introduction

The evolution of mobile networks is driven by increasing demands for enhanced data rates, ultra-low latency, and seamless integration of sensing and communication functionalities. Traditional networks have primarily focused on communication, treating sensing as a secondary concern[3]. However, 6G necessitates Joint Communications and Sensing (JCAS) to optimize spectral efficiency, improve system robustness, and enable advanced smart applications. By integrating both functions within the same infrastructure, JCAS eliminates the need for dedicated sensing hardware, reducing costs and energy consumption while maximizing spectrum utilization.

Coordinated Multipoint (CoMP) JCAS leverages CoMP transmission principles to enable collaborative sensing and signal sharing between multiple transmission/reception points (TRPs). Unlike standalone sensing, which relies on individual base stations or radar systems, CoMP JCAS facilitates distributed sensing by allowing multiple TRPs to cooperate in transmitting and receiving signals. This significantly improves sensing accuracy, enhances spatial coverage, and mitigates interference, leading to better performance in dense urban areas and complex environments.

The benefits of CoMP JCAS span intelligent transportation, industrial automation, security surveillance, and smart city applications[2]. In autonomous driving, high-resolution sensing enables real-time object detection and safer navigation, even in occlusions or low visibility. Industrial automation benefits from predictive maintenance, while security applications leverage distributed sensing for improved threat detection.

Additionally, CoMP JCAS addresses spectrum congestion and energy efficiency by minimizing hardware redundancy and power consumption. Advanced techniques like coordinated beamforming and interference management further optimize communication and sensing efficiency.

As 6G research progresses, implementing CoMP JCAS requires novel network architectures, efficient clustering, and enhanced TRP synchronization. Overcoming these challenges is crucial for unlocking

high-precision sensing and ultra-reliable communication. This paper explores CoMP JCAS network architectures, operational modes, and enabling technologies, providing a comprehensive analysis of its benefits and challenges in future 6G mobile networks.

CoMP JCAS Architecture and Operation

The implementation of Coordinated Multipoint Joint Communications and Sensing (CoMP JCAS) in 6G networks requires a robust architectural framework that ensures seamless integration of communication and sensing functionalities[4]. To achieve efficient operation, CoMP JCAS relies on two primary network structures: Cloud-Radio Access Network (C-RAN) and Distributed-Radio Access Network (D-RAN). Both architectures provide distinct advantages in terms of processing capabilities, coordination efficiency, and latency management.

Fig. 1: Comparison of D-RAN (left) and C-RAN (right) architectures. D-RAN employs localized BBUs near RRUs, reducing latency and improving real-time responsiveness. C-RAN centralizes BBUs in a BBU pool, enhancing coordination and resource efficiency but increasing fronthaul dependency.[3]

C-RAN offers centralized processing with cloud-based resource management, where multiple distributed transmission/reception points (TRPs) are connected to a centralized baseband processing unit[5]. This architecture enhances computational efficiency and scalability by allowing flexible resource allocation and dynamic workload distribution. By leveraging cloud computing and virtualization techniques, C-RAN facilitates rapid adaptation to varying network demands, optimizing both communication and sensing performance. However, its reliance on a centralized control unit introduces potential latency issues due to increased backhaul traffic, which may impact real-time sensing applications.

In contrast, D-RAN provides decentralized coordination with localized processing, where each TRP operates with its own processing unit, reducing latency and improving real-time responsiveness. This decentralized approach minimizes dependency on a central processing unit, making it more resilient to network failures and communication bottlenecks. Additionally, D-RAN is well-suited for applications requiring rapid sensing and immediate decision-making, such as autonomous driving and mission-critical surveillance. However, the lack of centralized control may lead to challenges in coordination and resource management, necessitating advanced synchronization techniques among TRPs

Moreover, C-RAN's centralized nature enables efficient spectrum sharing and interference management, enhancing overall network performance. On the other hand, D-RAN's distributed approach ensures greater fault tolerance and operational independence, making it ideal for ultra-reliable application[1]s. The trade-off between centralized efficiency and decentralized resilience highlights the need for hybrid architectures. Future research should explore adaptive frameworks that dynamically switch between C-RAN and D-RAN based on network conditions

(a) Multi-monostatic sensing (MMS). (b) Multi-bistatic sensing (MBS) (c) Multi-X-static hybrid sensing (MXS).

Fig. 2: Types of CoMP Sensing[1]

CoMP sensing can be categorized into three primary types based on how TRPs coordinate their sensing functions: Multi-Monostatic Sensing (MMS), Multi-Bistatic Sensing (MBS), and Multi-X-Static Hybrid Sensing (MXS). Each of these approaches has distinct trade-offs in terms of computational overhead, energy efficiency, and sensing accuracy[2], making them suitable for different applications.

1) Multi-Monostatic Sensing (MMS) In MMS, each TRP independently transmits and receives signals, functioning as an isolated sensing unit. This approach requires minimal coordination among TRPs, making it relatively simple to implement. However, due to the lack of cooperative sensing, MMS often results in redundant energy consumption, as each TRP must operate in full-duplex mode, continuously transmitting and receiving. While this method is beneficial for localized and independent analysis, it suffers from limited spatial diversity and is less effective in large-scale sensing applications where coordinated sensing is required for improved accuracy.

2) Multi-Bistatic Sensing (MBS) MBS optimizes sensing coverage and energy efficiency by allowing a single TRP to transmit while multiple TRPs act as passive receivers[3]. The receiving TRPs process reflections from the transmitted signal, enabling enhanced spatial awareness and increased detection accuracy. This method significantly improves sensing precision, as multiple perspectives on an object or environment lead to better localization and tracking. However, MBS requires precise synchronization between the transmitting and receiving TRPs to ensure coherent data processing. Any desynchronization can lead to errors in position estimation and increased computational complexity.

3) Multi-X-Static Hybrid Sensing (MXS) MXS combines the advantages of MMS and MBS by leveraging full-duplex communication capabilities. In this approach, a TRP simultaneously transmits and receives signals while neighboring TRPs also act as passive receivers[3]. This hybrid model enhances sensing accuracy by utilizing both monostatic and bistatic techniques. The additional reception channels improve spatial resolution and clutter suppression, making MXS particularly useful for applications such as high-precision localization and target tracking. However, like MBS, MXS also requires stringent synchronization mechanisms to ensure that the received signals are processed accurately and efficiently.

Trade-offs and Practical Considerations

Each CoMP sensing type presents unique trade-offs that must be considered based on the intended application:

MMS is ideal for scenarios where independent sensing is required, but it has high energy consumption and does not fully leverage cooperative sensing benefits. MBS provides superior coverage and improved accuracy but demands complex synchronization and data fusion techniques[4]. MXS achieves the highest accuracy by combining monostatic and bistatic sensing, but it requires full-duplex capability and advanced signal processing algorithms. The selection of an appropriate CoMP sensing strategy depends on multiple factors, including network topology, computational resources, application requirements, and energy con-

straints. Future 6G networks must integrate dynamic sensing configurations to adaptively switch between MMS, MBS, and MXS based on real-time environmental conditions and system demands.

Analysis of CoMP Sensing Performance in Coverage and Accuracy

Accuracy and coverage are two of the most essential performance metrics of a sensing system[5]. In Section III-B, we introduced three main types of CoMP sensing in future mobile networks and analyzed their pros and cons theoretically. However, experimental evaluation is necessary to assess system performance and the practical feasibility of CoMP sensing. In this section, we present a simulation-based analysis of coverage and accuracy issues. We also compare the results with conventional standalone radar sensing systems and highlight the advantages of CoMP sensing.

CoMP Sensing Coverage

Future mobile networks aim to provide seamless sensing services. However, modern mobile networks are designed primarily for communication coverage, while radar sensing coverage follows different constraints. Sensing signals generally experience higher attenuation due to reflection and scattering. Moreover, channel conditions depend on object properties such as material, roughness, and thickness. Research on coverage performance and techniques to extend sensing areas is crucial for applying CoMP sensing in mobile networks.

We evaluate the coverage performance of the three CoMP sensing types using a simulation with network-centric clustering[2]. Three TRPs are deployed 200 m apart in a two-dimensional plane. The system operates at 28 GHz in Frequency Range 2 (FR2) with a bandwidth of 400 MHz. The transmission power is set to 43 dBm, and the noise figure at the receiver is 5 dB. The radar cross-section (RCS) of objects is set to 10 dBsm for simplified analysis. The path loss (PL) is given by:

$$PL = \frac{G_T G_R \sigma \lambda^2}{(4\pi)^3 R_1^2 R_2^2},\tag{1}$$

where σ is the RCS, R_1 and R_2 represent the distances between the transmitter and reflector and between the reflector and receiver, respectively. For active sensing, $R_1 = R_2$.

We analyze the minimum signal-to-noise ratio (SNR) among the RPs to determine the cluster area where all TRPs are available. Figure 3 illustrates the SNR contours (0 dB and 5 dB) for MMS, MBS, and MXS. The contours reveal that MBS and MXS significantly extend the sensing area compared to MMS, which has a more confined coverage.

CoMP Sensing Accuracy

Distributed sensing significantly improves localization accuracy compared to standalone radar systems[3]. In the simulation, three coordinated TRPs are deployed 200 m apart, with a set of reflection points distributed within the cluster area. Standalone radar sensing is also simulated as a control case. The simulation assumes an isotropic antenna model for the CoMP sensing system.

The position of the targets is estimated using the least square method:

$$\min F(x_0, y_0, z_0), \quad \text{where} \quad (x_0, y_0, z_0) \in \mathbb{R}.\tag{2}$$

The mean absolute error (MAE) is used to evaluate sensing accuracy:

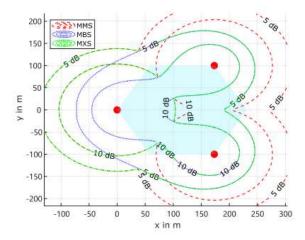$$MAE = \frac{1}{N} \sum_{r=1}^{N} \sqrt{(x_0 - x_r)^2 + (y_0 - y_r)^2 + (z_0 - z_r)^2},\tag{3}$$

Fig. 3: Comparison of CoMP Sensing Coverage Across Different Types[5]

where (x_r, y_r, z_r) is the true position of the target, and N represents the number of target points.

Results indicate that CoMP sensing significantly reduces MAE compared to standalone radar systems. Among CoMP sensing modes, MMS provides the best accuracy due to the superior range resolution of active sensing. MXS achieves better performance than MBS due to the additional reception per transmission. However, sensing accuracy diminishes when TRPs are spaced closer than 50 m, mainly due to angle estimation errors. This issue can be mitigated by adjusting TRP heights or using directional antennas.

In conclusion, CoMP sensing enhances coverage and accuracy, making it a promising approach for 6G mobile networks[1]. The trade-offs between energy consumption, synchronization complexity, and sensing precision must be carefully balanced to optimize performance across different application scenarios.

Challenges and Future Directions

Despite the promising advantages of CoMP JCAS, several challenges need to be addressed for widespread adoption in 6G networks. Synchronization and coordination among TRPs must be refined to maintain phase coherence and avoid latency issues. AI-driven clustering techniques can dynamically adapt TRP clusters, optimizing performance while reducing computational overhead. Security and privacy concerns must also be tackled, as the integration of sensing introduces new vulnerabilities related to data security and unauthorized access.

Another critical aspect is the role of edge computing in CoMP JCAS. Deploying Multi-Access Edge Computing (MEC) solutions can enhance real-time processing capabilities and reduce latency, making CoMP JCAS more viable for mission-critical applications such as healthcare and emergency response[4]. Future research should focus on refining AI algorithms for adaptive clustering, optimizing power efficiency, and ensuring secure communication channels in 6G CoMP JCAS networks.

Conclusion

CoMP JCAS presents a transformative shift in mobile network design, enabling simultaneous sensing and communication. Our analysis highlights its potential to enhance coverage, mitigate interference, and optimize resource utilization in 6G networks. By leveraging coordinated multipoint techniques, CoMP JCAS ensures seamless connectivity and improved spectral efficiency.

Future advancements in AI-driven clustering, real-world deployment scenarios, and security-enhanced CoMP JCAS implementations will further elevate its effectiveness. The integration of edge intelligence and adaptive beamforming will play a crucial role in refining its performance. As 6G technology continues to evolve, CoMP JCAS is poised to become an essential component in smart infrastructure, connected autonomous systems, and next-generation communication frameworks.

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ROBOTICS

ELECTRONICS SKIN FOR VIRTUAL AND SENSATION GENERATION IN IMMERSIVE VIRTUAL AND AUGMENTED REALITY

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Abstract

Virtual Reality (VR) and Augmented Reality (AR) have gained global attention due to their ability to enhance digital interactions. The key to immersive AR/VR experiences lies in delivering comprehensive sensory feedback. While visual and auditory feedback is well-integrated into current AR/VR systems, haptic feedback remains a challenge. Electronic skin (e-skin) has emerged as a potential solution to enhance haptic sensations in AR/VR. It features compact, lightweight, and highly flexible structures that can seamlessly adhere to the body, mimicking natural touch and thermal sensations. The integration of nanomaterials, flexible electronics, and AI-driven adaptation mechanisms has enabled significant advancements in e-skin technology. This paper explores recent developments, applications, and the future potential of e-skin in enhancing user immersion in digital environments.

Introduction

Virtual Reality (VR) and Augmented Reality (AR) have gained global attention for their ability to create highly immersive digital experiences. The key to successfully implementing these technologies lies in providing users with rich sensory input that enhances their perception of the virtual world. While visual and auditory feedback has been seamlessly integrated into most AR/VR systems, haptic feedback remains a challenge[3]. Current wearable systems often rely on rigid and bulky components, which can disrupt immersion, particularly in touchless interactions where users engage with virtual objects without physically touching them but still expect to perceive sensations such as force, temperature, and texture.

Electronic skin (e-skin) has emerged as a revolutionary technology that addresses these limitations by offering a compact, lightweight, and highly flexible alternative to traditional haptic systems. Unlike conventional haptic devices, e-skin mimics the properties of human skin, allowing it to conform seamlessly to the body and provide realistic touch sensations[4]. Recent advancements in nanomaterials, flexible electronics, and microfabrication techniques have enabled e-skin to simulate a variety of sensory experiences, including pressure, vibrations, and temperature variations. Furthermore, e-skin extends human perception beyond conventional limits by enabling virtual olfaction, allowing users to experience scents in AR/VR environments, and magnetoreception, providing a sense of direction and spatial awareness through interactions with magnetic fields.

As e-skin technology continues to evolve, its applications extend beyond gaming and entertainment to fields such as remote healthcare, telepresence, education, and virtual training. For example, in medical applications, e-skin can enable doctors to perform remote diagnostics by simulating the sense of touch in real-time AR/VR interfaces. In education, it can provide students with hands-on virtual learning experiences that mimic real-world sensations. With its ability to bridge the gap between the physical

and digital worlds, e-skin is poised to become a fundamental component of next-generation AR/VR systems, unlocking new possibilities for immersive interaction and redefining how users engage with virtual environments.

E-Skin for Virtual Sensations

E-skin plays a crucial role in the fields of virtual reality (VR) and augmented reality (AR), with its most prominent application being touchless interaction[1]. This advanced technology enables users to experience a simulated sense of touch, known as haptic feedback, as well as virtual thermoception, which allows them to perceive temperature variations in a digital environment. Through e-skin, users can sense different textures, levels of hardness, and surface roughness, enhancing their interaction with virtual objects.

The primary mechanisms enabling touchless interaction through e-skin include magnetic fields, electromagnetic induction, electrostatics, and electrical stimulation. These technologies work together to create a realistic and immersive experience by mimicking the natural sensations of touch without requiring direct physical contact. Additionally, e-skin technology ensures that these interactions are painless and non-invasive, making it an effective tool for enhancing user experience in VR and AR applications. As research and innovation in this field continue to advance, e-skin is expected to revolutionize the way humans interact with digital environments, bringing virtual experiences closer to reality.

Virtual Haptic Experience

The advancement of VR and AR heavily depends on the ability to create realistic virtual tactile experiences[4]. While traditional devices like handheld controllers, exoskeletons, and gloves have been used, achieving a highly immersive touch experience requires more advanced solutions that meet strict criteria for speed, resolution, size, and biocompatibility. Inspired by natural mechanoreceptors, modern e-skins generate virtual tactile sensations using non-contact methods that mimic real skin stimulation. The most common approaches include mechanical vibration and electrical stimulation, both of which enhance user interaction with virtual environments.

Mechanical vibration-based e-skins primarily use haptic actuators to generate tactile sensations, driven by mechanisms like magnetic fields, electrical motors, pneumatics, and hydraulics. These actuators, controlled by integrated circuits, create programmable spatiotemporal patterns for diverse tactile effects. Notable developments include wireless haptic interfaces with magnetic actuator arrays for VR and AR applications, soft e-skins with high-resolution mechanical actuator arrays for enhanced tactile recognition, and stretchable electrostatic actuators for precise texture and shape recognition. Despite these advancements, creating compact, high-resolution actuator arrays remains a significant challenge IN fig[1].

Electrical stimulation-based e-skins apply weak electrical currents to the skin, activating sensory nerves that transmit signals to the brain, simulating tactile experiences[2]. Innovations in this field include self-powered electro-tactile systems using Triboelectric Nanogenerators (TENGs), high-resolution e-skins with electroactive rendering systems, and soft electrotactile interfaces like the WeTac system, which delivers programmed tactile feedback. While these systems offer high resolution and compact designs, challenges such as variations in skin impedance and potential discomfort from improper voltage levels continue to hinder their widespread adoption.
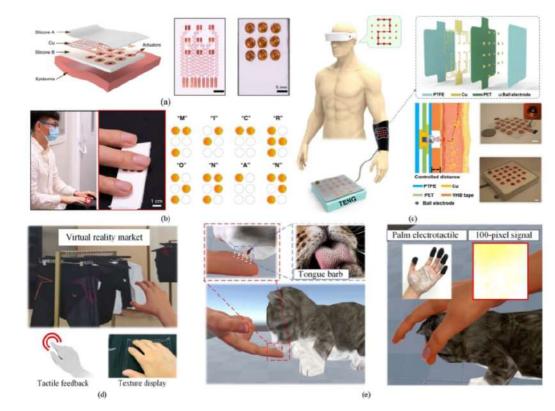
Fig. 1: E-skins for virtual skin-related perception. (a) Design of the mini vibrotactile actuators and e-skin. (b) Braille recognition based on the e-skin in (a). Reproduced with permission , Springer Nature. (c) Schematic illustration of skin-integrated electro-tactile interface and exploded view and optical image of the electrode array, the American Association for the Advancement of Science. (d) and (e) Applications of the electrotactile rendering system. (d) Feeling the touch and texture of clothes in VR shopping. (e) Feel a sense of itch in the finger by a virtual cat and a sense of petting a virtual cat through the palm electrotactile device, the American Association for the Advancement of Science.[2]

Virtual Temperature Experience

Thermal perception plays a crucial role in interpreting environmental changes, complementing haptic feedback in virtual experiences. When exposed to temperature variations, thermoreceptors generate impulse signals that the brain processes as warmth or cold. While haptic feedback has advanced significantly in VR and AR, replicating precise thermal sensations through e-skin remains a challenge due to the complexity of miniaturizing and softening temperature control systems while ensuring rapid and precise thermal modulation.

Although a few studies have explored thermal e-skins, practical applications remain limited. R. C. Webb et al. developed an e-skin with micro-heaters, but it has yet to be integrated into VR or AR. Y. Xu et al[1]. introduced a passive cooling e-skin using porous SEBS substrates to reflect sunlight and minimize heat absorption, but it lacked active temperature control. The primary challenge lies in achieving a balance between heating and cooling functions while maintaining flexibility, wearability, and responsiveness for real-time virtual interactions.

Recent advancements show promise in overcoming these limitations. S. Kim et al. developed a thermal display glove with Thermoelectric Devices (TEDs) that used the Peltier effect to provide bidirectional temperature adjustments during VR interactions[4]. Similarly, J. Lee et al. created a soft, stretchable e-skin capable of generating instant hot and cold sensations through thermoelectric pellets and a PID feedback control system. While initially integrated into gloves, these technologies could lead to next-generation e-

skins that seamlessly combine haptic and thermal feedback, enhancing immersive experiences in gaming, prosthetics, and medical simulations

Virtual Olfactory Experience

Beyond simulating tactile and thermal sensations, e-skins have the potential to replicate other sensory experiences, including olfaction. The sense of smell plays a vital role in human perception, significantly enhancing immersion in VR and AR environments[4]. However, creating virtual olfactory sensations presents challenges, as saturating an entire space with odors is impractical, and requiring users to wear bulky equipment for extended periods would be uncomfortable. Recently, e-skin technology has emerged as a promising solution for integrating scent into virtual experiences.

Y. Liu et al. introduced a three-layer, skin-interfaced virtual olfactory feedback system using an array of Odor Generators (OGs). These OGs produced distinct scents by precisely controlling the melting and solidification of a paraffin and liquid perfume mixture through a thermistor. The emitted odor concentration was regulated using programmable Metal-Oxide-Semiconductor Field Effect Transistors (MOSFETs), ensuring efficient control. This olfactory interface demonstrated exceptional response speed, stability, and power efficiency, enabling users to engage in virtual interactions enriched with realistic scent-based feedback.

Beyond thermistor-based paraffin melting, several other techniques have been explored for virtual olfactory generation. These include free emission, ultrasonic atomizers, vapor pressure-controlled air turbulence, electrostatic field evaporation, and Peltier heating elements[1]. Despite these advancements, the primary challenge lies in adapting these methods into a miniaturized, flexible, and wearable format. Overcoming this complexity is essential for integrating olfactory feedback seamlessly into future e-skin technologies, further enhancing the realism of immersive digital environments.

Directional Perception

Magnetoreception is the ability to detect the Earth's magnetic field, primarily used for orientation and navigation. While humans are not known to possess this ability naturally, wearable magnetosensitive e-skins have been developed to provide proximity and direction-sensing capabilities, enhancing immersive experiences in VR and AR. M. Melzer et al. introduced a flexible electronic system attached to the skin that detects magnetic fields using Bismuth-based Hall sensors. These sensors, created by depositing bismuth films onto electrical contacts on flexible foils, allowed the visualization of a finger's position relative to a permanent magnet, demonstrating potential applications in virtual environments.

Early magnetosensitive e-skins relied on external magnetic fields for operation. G. S. C. Bermúdez and his research team made a breakthrough by developing an e-skin compass integrated with anisotropic magnetoresistive (AMR) sensors. This device, built on a 100-nm-thick gold-based Wheatstone bridge fabricated on ultra-thin Mylar foils, featured AMR sensors conditioned using the barber pole method[3]. The e-skin demonstrated exceptional sensitivity, detecting geomagnetic fields with a range between 40–60 μT, remarkable flexibility, and durability, maintaining full functionality even after 2,000 bending cycles. It successfully enabled users to control virtual elements through hand motions within the geomagnetic field, though it did not provide an actual sense of direction.

Fig. 2: E-skins for virtual olfactory experience and magnetoperception. (a) and (b) Architectures of the olfaction interfaces. (a) Schematic diagram of the olfaction interface and its application in VR experience. The schematic illustration in the frame shows an exploded view of the odor generators. (b) Optical images of the olfaction interface mounted onto a human, Springer Nature. (c) Schematic of a 5 × 5 magneto-interactive display array[3]

To address this limitation, S. W. Lee et al. developed a magneto-interactive electroluminescence (EL)-based e-skin capable of visualizing magnetic field information[1]. The device incorporated a layered structure with ZnS: Cu/poly (vinylidene fluoride-tri-fluoroethylene-chlorofluoroethylene) (PVDF-TrFE-CFE) and a magnetoactive conductive fluid made of multi-walled carbon nanotubes (MWNTs) decorated with superparamagnetic iron oxide (Fe_3O_4) nanoparticles. When an external magnetic field was applied, the device created a conductive channel, allowing for real-time visualization and storage of magnetic data. While these innovations mark significant progress in directional perception, further advancements are needed to develop even more immersive and user-friendly interaction modes in VR and AR.

Challenges and Future Prospects

In the previous sections, we explored the crucial role of e-skin in enhancing immersion and interactivity within VR and AR environments. E-skin technology has advanced significantly, enabling tactile, thermal, olfactory, and directional sensations that transform digital experiences. Research into virtual multi-perception e-skins has been gaining momentum, with Y. H. Jung et al. introducing a wireless haptic interface capable of delivering multiple sensory experiences, including touch, directional perception, and hearing. This interface used vibrohaptic actuators to provide navigation guidance, play music, and offer feedback for prosthetic control. The ability of a single e-skin device to generate various sensory perceptions greatly enhances user engagement and interaction.

Beyond entertainment, e-skin technology holds transformative potential in fields such as medicine,

education, and industry. While gaming has been an early adopter, applications in medical simulations, educational training, and remote industrial operations could benefit from its tactile feedback and sensory immersion. Additionally, e-skin's touchless control capabilities make it useful in environments where physical interaction is impractical or unsafe. The emerging metaverse also presents exciting possibilities, as e-skin can bridge the gap between physical and digital worlds by providing realistic sensory experiences that align with the concept of a digital twin.

However, several challenges and opportunities arise as e-skin technology progresses. A primary concern is security and privacy, as the collection and transmission of sensory data—such as touch, temperature, and olfactory information—raise ethical considerations[2]. Ensuring secure data handling and user consent mechanisms is essential. Moreover, research on e-skin remains relatively limited compared to established sensory modalities like vision and hearing. Expanding research efforts to address e-skin-specific challenges will be key to its broader adoption. Standardization and interoperability also pose challenges, as common protocols for e-skin devices and data formats are necessary for seamless integration into VR and AR platforms. Establishing these standards would allow developers to create applications that fully leverage e-skin's capabilities, accelerating its widespread adoption.

Conclusion

In conclusion, e-skin technology has significantly advanced the immersive experience in VR and AR by enabling touchless interaction and replicating various sensory perceptions, including tactile, thermal, olfactory, and directional sensations. Beyond gaming and entertainment, its applications extend to critical fields such as healthcare, education, and industry, where it can enhance medical simulations, training programs, and remote operations. Additionally, the integration of e-skin into the metaverse presents exciting possibilities, allowing users to engage with digital environments in a more realistic and intuitive manner. As research progresses, advancements in miniaturization, flexibility, and integration will drive the widespread adoption of e-skin, making virtual interactions more seamless and lifelike. However, challenges such as security, privacy concerns, and standardization must be addressed to ensure safe and efficient implementation across various platforms. By overcoming these obstacles, e-skin has the potential to redefine human-computer interaction, blurring the lines between the physical and virtual worlds and unlocking new dimensions of immersive experiences.

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ROBOTICS AND AUTOMATION

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Introduction

Robotics and automation have become pivotal forces in shaping modern industries, transforming the way tasks are performed and reimagining traditional workflows. Robotics involves the design, construction, and operation of intelligent machines capable of performing tasks autonomously or semi-autonomously[1]. Automation, on the other hand, refers to the use of technology to minimize human intervention in processes, resulting in enhanced efficiency, consistency, and scalability.The convergence of these fields has unlocked unprecedented opportunities across a diverse range of sectors, including manufacturing, healthcare, agriculture, logistics, and even domestic applications. From automated assembly lines to surgical robots and autonomous vehicles, these technologies have demonstrated their ability to improve accuracy, reduce costs, and address labor shortages. This paper delves into the fundamental aspects of robotics and automation, covering their components, applications, challenges, and future prospects.

Robotics

Robotics involves the development and application of robots—mechanical devices that can perform physical tasks autonomously or semi-autonomously.

A. Key Components of Robotics

1.Hardware

- **Actuators and Sensors**: Actuators provide movement, while sensors allow robots to perceive their surroundings. These include force sensors, proximity sensors, LiDAR, and vision-based sensors.
- **Controllers**: The brain of the robot, responsible for processing data from sensors and sending commands to actuators to complete tasks efficiently[2].
- **Frames**: The mechanical structure of robots, designed for stability, strength, and adaptability to different working conditions.
- **Power Supply**: Provides energy to the robot, either through batteries, solar energy, or direct electrical supply.

2.Software

- **Artificial Intelligence (AI) and Machine Learning (ML)**: These technologies allow robots to learn from data, recognize patterns, and make informed decisions to adapt to their environment.
- **Robot Operating Systems (ROS)**: Open-source middleware that facilitates communication between different robotic components, simplifying the development process[3].
- **Computer Vision**: Enables robots to interpret and process visual data for applications like object detection, facial recognition, and autonomous navigation.
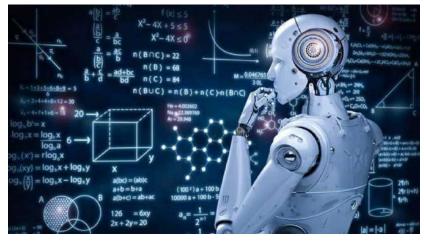
Fig. 1: Robotic process Automation(Courtesy :Researchgate)

- **Path Planning Algorithms**: Help robots navigate efficiently, avoiding obstacles and optimizing movement patterns.

Applications of Robotics

- **Industrial Robots**: Used in manufacturing to automate tasks such as welding, painting, assembly, and material handling, increasing efficiency and precision.
- **Medical Robots**: Assist in surgeries (e.g., the da Vinci surgical system), rehabilitation therapy, diagnostics, and patient monitoring.
- **Autonomous Vehicles**: Self-driving cars and drones that rely on robotic technology to operate safely and efficiently in complex environments[3].
- **Service Robots**: Robots used in customer service, security, cleaning, and personal assistance (e.g., robotic vacuum cleaners, humanoid service robots).
- **Space Exploration**: NASA and other space agencies use robots for planetary exploration, satellite maintenance, and deep-space missions.

Automation

Automation involves using technology to execute tasks with minimal human intervention, improving efficiency, consistency, and productivity in various industries.

Types of Automation

- **Fixed Automation**: Applied in mass production where tasks are repetitive and highly structured, such as car assembly lines.
- **Programmable Automation**: Allows reconfiguration of machines for different production processes, commonly used in batch production.
- **Flexible Automation**: Advanced automation systems that dynamically adapt to changes in production without requiring reprogramming[1].
- **Intelligent Automation**: Incorporates AI and ML to enable systems to make autonomous decisions, analyze data, and optimize workflows.

Fig. 2: Automation

Future Prospects of Robotics and Automation

The future of robotics and automation is driven by advancements in AI, ML, IoT, and edge computing.

Emerging Trends
- **Collaborative Robots (Cobots)**: Designed to work alongside humans in manufacturing and service industries, improving efficiency and safety.
- **AI-Powered Robots**: Equipped with advanced decision-making capabilities, allowing them to interact with humans and environments in a more intuitive way.
- **Swarm Robotics**: A system of multiple small robots working collectively to complete complex tasks, inspired by nature[2].
- **Autonomous Delivery Systems**: Robots and drones used for package deliveries, medical supplies transport, and retail automation.
- **Ethical and Social Considerations**: As robots become more integrated into society, discussions on job displacement, security risks, and ethical AI development continue to shape the future.

Challenges and Considerations
- **Job Displacement**: While automation enhances productivity, it raises concerns about workforce transition and reskilling.
- **Cybersecurity Risks**: Automated systems are vulnerable to cyberattacks, requiring robust security frameworks.
- **High Initial Investment**: Implementing robotic systems requires substantial capital investment, limiting accessibility for small businesses.
- **Regulatory and Ethical Challenges**: The development and deployment of autonomous systems must adhere to safety standards, privacy regulations, and ethical guidelines.
- **Technical Limitations**: Despite advancements, robots still struggle with complex decision-making, adaptability, and handling unpredictable environments.

Conclusion

Robotics and automation are revolutionizing industries, improving efficiency, safety, and productivity. With continued technological advancements, these fields will play a crucial role in shaping the future workforce, economy, and society. While challenges such as job displacement, security threats, and ethical concerns persist, strategic planning and human-machine collaboration will ensure a balanced and sustainable integration of automation technologies.

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ADVANCEMENTS IN HAPTIC MAGNETISM FOR INTERACTIVE TECHNOLOGIES

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Abstract

Haptic Magnetism, a novel concept in human-computer interaction, redefines the way users interact with technology by employing tactile feedback to simulate pseudo-magnetic forces such as attraction and repulsion. This emerging modality enables users to sense and interact with distant objects through carefully designed tactile stimuli, providing an intuitive, immersive, and non-contact interface. By leveraging these principles, Haptic Magnetism finds applications in diverse fields such as augmented reality, robotics, assistive technologies, and gaming.

The ability to deliver sensations of objects at a distance transforms traditional haptic systems by focusing on non-contact feedback rather than physical touch. This paper explores the technical principles behind Haptic Magnetism, evaluates its practical implementations, and highlights its ability to enhance human-computer interaction. Furthermore, the challenges faced by existing haptic devices, including limitations in resolution, spatial precision, and user adaptation, are discussed in detail. Future prospects, such as integrating machine learning for adaptive feedback and deploying advanced ultrasonic and wearable haptic devices, promise to address these limitations and unlock new possibilities for innovation.

By offering a detailed insight into this transformative technology, the paper envisions a future where Haptic Magnetism becomes a cornerstone of interactive systems, providing a seamless, immersive, and highly intuitive experience for users across various domains.

Introduction

Human-computer interaction (HCI) has evolved significantly over the past decade, with advancements in tactile feedback systems revolutionizing how users engage with virtual and physical environments. Among these innovations, Haptic Magnetism stands out as a transformative modality that enables interactions with distant objects through tactile sensations mimicking pseudo-magnetic forces such as attraction and repulsion. Figure 1 illustrates this concept, where users experience dynamic tactile feedback to guide, attract, or repel their actions.

At the core of Haptic Magnetism is its ability to create an immersive sensory experience using generic haptic devices. These devices generate tactile feedback that adapts to the user's movements, creating the illusion of attraction or repulsion based on the distance and orientation relative to a virtual or physical object[5]. This concept not only enhances user interaction but also broadens the possibilities for integrating haptics into emerging technologies like augmented reality (AR), virtual reality (VR), and assistive devices.

For instance, in augmented reality applications, Haptic Magnetism can guide users toward occluded objects or important points of interest, creating a more intuitive navigational experience. Similarly, in robotics and teleoperation, the technology enhances precision and control by providing operators with

Fig. 1: Illustration of Haptic Magnetism: A user interacts with distant objects using tactile feedback simulating pseudo-magnetic forces such as attraction and repulsion[2].

tactile cues for manipulating remote objects. Beyond these domains, it offers significant potential for gaming, medical simulations, and accessibility solutions, where tactile feedback can improve realism, engagement, and inclusivity.

This paper explores the underlying principles of Haptic Magnetism, evaluates its applications, and discusses its technical challenges[1]. Additionally, we highlight the current limitations of existing haptic systems, including device resolution and user adaptation, and propose future directions for advancing this technology. By addressing these aspects, Haptic Magnetism has the potential to reshape the future of human-computer interaction, offering a seamless and intuitive interface for users in both virtual and real-world environments.

Principles of Haptic Magnetism

Haptic Magnetism operates on three foundational principles that define its unique approach to tactile feedback and interaction:

- **Tactile Stimulation:** At the heart of Haptic Magnetism is the generation of tactile sensations that mimic pseudo-magnetic forces. Generic haptic devices, such as vibration motors[2], haptic gloves, and ultrasonic systems, create sensations of attraction or repulsion without requiring physical contact. These stimuli are designed to engage the user's sense of touch in novel ways, enhancing interaction with both virtual and physical environments.
- **Distance-Based Feedback:** The intensity, frequency, or pattern of tactile feedback dynamically changes based on the user's relative position to a distant object. For instance, as a user's hand approaches a virtual object, the sensation of attraction may intensify, while moving away from the object reduces the feedback. This dynamic nature allows users to sense objects at a distance and adjust their movements intuitively.
- **Pseudo-Magnetic Interactions:** Haptic Magnetism leverages the principles of attraction and repulsion to enable interactions such as guidance, nudging, and discovery. These interactions provide users with directional cues, allowing them to locate hidden objects, avoid hazards, or interact with virtual elements in augmented and virtual reality scenarios[1]. The use of pseudo-magnetic forces creates a seamless and immersive experience.

Fig. 2: Core principles of Haptic Magnetism: tactile stimulation, dynamic distance-based feedback, and pseudo-magnetic interactions[6]

The principles outlined above are depicted in Figure 2, showcasing the interaction flow where tactile feedback intensifies or diminishes based on user actions and proximity to objects. These principles form the foundation for designing advanced haptic systems that deliver intuitive and immersive user experiences.

Applications of Haptic Magnetism

Haptic Magnetism's versatility allows it to be applied across various domains, enhancing human-computer interaction in innovative ways:

- **Augmented Reality (AR) and Virtual Reality (VR):** Haptic Magnetism significantly improves AR and VR experiences by providing intuitive tactile cues[4]. For example, users can be guided toward hidden objects in augmented reality environments or receive feedback that enhances their immersion in virtual reality simulations. This makes navigation and interaction in digital spaces more engaging and efficient.
- **Assistive Technologies:** For individuals with visual impairments, Haptic Magnetism can act as a navigational aid. By delivering directional cues through tactile feedback, users can detect obstacles, find objects, and safely navigate unfamiliar environments. This technology holds promise for improving accessibility and inclusivity in digital and physical spaces.
- **Robotics and Teleoperation:** Haptic Magnetism enhances precision and control in robotic systems, particularly in teleoperation tasks where tactile feedback helps operators manipulate objects remotely[1]. For instance, in surgical robotics, pseudo-magnetic sensations can provide surgeons with real-time feedback for delicate procedures, ensuring accuracy and safety.
- **Gaming and Entertainment:** Immersive gaming experiences are revolutionized by Haptic Magnetism, where players can feel interactive forces guiding their actions. This tactile dimension adds a new layer of engagement, allowing players to experience virtual worlds with greater realism and depth.
- **Industrial and Collaborative Robotics:** In collaborative workspaces, Haptic Magnetism can ensure safety and efficiency by alerting workers about hazardous zones or guiding robots to execute precise tasks[5]. Tactile cues improve human-robot collaboration by creating intuitive interfaces for communication.

As shown in Figure 3, Haptic Magnetism serves as a versatile tool for diverse applications, ranging from immersive digital environments to real-world scenarios. These applications demonstrate its potential to transform industries by creating intuitive, tactile-driven interactions.

Fig. 3: Applications of Haptic Magnetism across AR, VR, assistive technologies, robotics, and gaming(Courtesy : ResearchGate)

Challenges in Haptic Magnetism

Despite its immense potential, Haptic Magnetism faces several challenges that must be addressed to realize its full capabilities:

- **Device Limitations:** Current haptic devices struggle with delivering high-resolution, precise tactile feedback over large interaction areas. Limitations in hardware, such as vibration motors or ultrasonic transducers, restrict the intensity and realism of pseudo-magnetic forces. Additionally, wearable haptic systems often suffer from bulkiness and limited battery life, hindering portability and usability.
- **Data Collection and Quality:** Developing effective haptic feedback models requires high-quality data. Collecting diverse datasets that capture user interactions across various environments and scenarios is challenging[3]. Furthermore, ensuring the accuracy and reliability of this data for training machine learning models adds an additional layer of complexity.
- **User Adaptation and Learning Curve:** Users may find it difficult to interpret pseudo-magnetic cues intuitively, especially when first introduced to the technology. Training users to understand and respond to the tactile sensations effectively is crucial for ensuring seamless adoption. Additionally, individual differences in tactile perception pose challenges for creating universally effective haptic systems.
- **Adversarial Interference:** In sensitive applications such as robotics or assistive technologies, external environmental factors like vibrations or electromagnetic interference can disrupt haptic feedback[4]. These interferences may lead to inaccuracies, posing risks in critical tasks such as surgery or navigation.
- **Cost and Scalability:** Advanced haptic devices that can replicate pseudo-magnetic forces are often expensive to design and manufacture. Scaling these technologies for mass adoption in consumer markets remains a significant challenge, especially for industries with budget constraints.

The key challenges faced by researchers and developers in advancing Haptic Magnetism. Addressing these issues requires a multidisciplinary approach involving advancements in hardware, machine learning, and user-centered design principles.

Future Directions

The future of Haptic Magnetism lies in its integration with cutting-edge technologies and its application in a broader range of domains. Advancements in hardware, software, and user-centric design promise to unlock new possibilities for this transformative modality. Key areas of exploration include:

- **Advancements in Wearable Haptics:** Next-generation wearable devices, such as lightweight haptic gloves and wristbands, are being developed to deliver more precise and natural tactile feedback[5]. These devices aim to enhance comfort, portability, and usability, making Haptic Magnetism accessible for everyday applications.
- **Integration with Artificial Intelligence:** Machine learning and AI algorithms can be used to personalize haptic feedback based on individual user preferences and interaction contexts. By analyzing user behavior, AI-powered systems can dynamically adjust feedback intensity and patterns, improving the intuitiveness and effectiveness of Haptic Magnetism.
- **Enhanced Multimodal Interfaces:** Future systems are likely to combine Haptic Magnetism with other sensory modalities, such as visual and auditory feedback, to create fully immersive experiences. For example, augmented reality applications could integrate tactile cues with visual overlays to guide users more effectively.
- **Medical and Training Simulations:** Haptic Magnetism has immense potential in medical training, where it can simulate realistic tactile sensations during surgical procedures. Similarly, it can be used in virtual training environments to replicate real-world interactions, improving skill acquisition and performance.
- **Expanded Use in Collaborative Robotics:** In industrial and collaborative robotics, Haptic Magnetism can improve safety and efficiency by providing tactile feedback that enhances human-robot collaboration. For instance, workers in a factory setting can receive haptic cues about the robot's intentions or potential hazards in real-time.
- **Ultrasonic and Spatial Haptics:** Ultrasonic technologies, which create tactile sensations using focused sound waves, are expected to play a significant role in advancing Haptic Magnetism. These systems enable non-contact tactile feedback over larger distances, expanding the range of interactions.
- **Cost-Effective Solutions:** Efforts are underway to develop low-cost haptic systems that maintain high performance and accessibility[6]. This is critical for scaling Haptic Magnetism in consumer markets, particularly in gaming, education, and assistive technologies.

The potential advancements in Haptic Magnetism span multiple domains and technologies. By addressing current challenges and leveraging emerging innovations, this field is poised to revolutionize human-computer interaction, creating more intuitive, immersive, and effective systems.

Conclusion

Haptic Magnetism represents a paradigm shift in human-computer interaction by introducing pseudo-magnetic tactile feedback as a novel and intuitive method of engaging with both virtual and physical environments. This technology bridges the gap between users and distant objects, enabling seamless, immersive interactions that were previously unattainable with traditional haptic systems.

The core principles of Haptic Magnetism—tactile stimulation, dynamic distance-based feedback, and pseudo-magnetic interactions—form the foundation for its transformative potential. Applications across augmented reality, robotics, assistive technologies, and gaming highlight its versatility and its ability to enhance user experiences in diverse domains. Moreover, advancements in wearable haptics, AI-powered personalization, and ultrasonic feedback systems promise to address current limitations, paving the way for scalable and cost-effective solutions.

However, challenges such as device limitations, data quality, and user adaptation must be addressed to unlock the full capabilities of Haptic Magnetism. Multidisciplinary collaboration among researchers,

engineers, and designers will play a crucial role in overcoming these barriers. Additionally, ethical considerations and accessibility must remain central to the development of this technology to ensure its benefits are inclusive and sustainable.

As this field continues to evolve, Haptic Magnetism has the potential to revolutionize how humans interact with technology, fostering a future where tactile feedback becomes an integral part of immersive experiences. By bridging sensory gaps and creating intuitive interfaces, Haptic Magnetism promises to reshape industries and redefine the boundaries of human-computer interaction.

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RENEWABLE ENERGY

GREEN HYDROGEN PRODUCTION: A CLEAN FUEL ALTERNATIVE

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Abstract

Green hydrogen, produced through electrolysis powered by renewable energy sources, is emerging as a key solution in the global transition to sustainable energy. Unlike conventional hydrogen derived from fossil fuels, green hydrogen is entirely carbon-free, making it a crucial alternative for decarbonizing industries, transportation, and energy storage. Its potential to replace coal and natural gas in heavy industries, serve as a clean fuel for long-haul transport, and store excess renewable energy enhances both environmental sustainability and energy security. Despite challenges such as high production costs, infrastructure limitations, and efficiency concerns, ongoing technological advancements and international investments are driving the widespread adoption of green hydrogen. As the world moves toward net-zero emissions, green hydrogen stands as a transformative energy source that will play a vital role in shaping a cleaner and more resilient future.

Introduction

As the world shifts towards sustainable energy solutions, green hydrogen has emerged as a promising alternative to fossil fuels. Unlike conventional hydrogen, which is produced using natural gas and emits carbon dioxide, green hydrogen is generated through electrolysis powered by renewable energy sources such as wind and solar. This method ensures a completely clean production process, making green hydrogen a key player in reducing global carbon emissions. With growing concerns over climate change and energy security, the adoption of green hydrogen presents an opportunity to transform the way industries, transportation, and power generation operate.

One of the most remarkable aspects of green hydrogen is its ability to decarbonize hard-to-abate sectors. Industries such as steel, cement, and chemicals, which rely heavily on fossil fuels, can transition to hydrogen-based energy, significantly reducing their carbon footprint. Additionally, green hydrogen offers a sustainable alternative for transportation, particularly for heavy-duty vehicles, ships, and airplanes, where battery-electric solutions face limitations. Its role in energy storage is also crucial, as it enables the efficient use of surplus electricity generated from renewable sources, helping to stabilize power grids and ensure a reliable energy supply.

Despite its advantages, green hydrogen still faces several hurdles, including high production costs, infrastructure challenges, and energy conversion inefficiencies. However, with rapid advancements in electrolysis technology and increased government support, the cost of green hydrogen is expected to decrease in the coming years. Many countries and corporations are already investing heavily in hydrogen projects, recognizing its potential to accelerate the transition to a carbon-neutral economy. As innovation continues to drive progress, green hydrogen is set to become a cornerstone of the clean energy revolution, paving the way for a sustainable and resilient future.

Fig. 1: Green hydrogen generation[1]

Importance and Applications of Green Hydrogen

Green hydrogen is gaining global attention due to its ability to replace fossil fuels in various industries, leading to a cleaner and more sustainable future. Its versatility allows it to be used across multiple sectors, making it a crucial element in the global transition to renewable energy. Below are its key applications and their significance.

1. Decarbonizing Industries

Industries such as steel, cement, and chemical manufacturing are among the largest carbon emitters due to their heavy reliance on coal, natural gas, and other fossil fuels. These industries require extremely high temperatures for production processes, making direct electrification challenging. Green hydrogen provides a clean alternative by serving as a high-energy fuel that can replace coal in steelmaking, power cement kilns, and be used as a feedstock in chemical production. For example, in steel manufacturing, green hydrogen can replace coke (a carbon-heavy fuel derived from coal) in Direct Reduced Iron (DRI) technology, producing steel without emitting carbon dioxide. Similarly, in chemical industries, green hydrogen is essential for the production of ammonia and methanol, which are widely used in fertilizers and other industrial applications. By integrating green hydrogen into these industries, global emissions can be significantly reduced, supporting the transition to a low-carbon economy.

2. Transportation Revolution

The transportation sector is one of the biggest contributors to carbon emissions, primarily due to the widespread use of gasoline and diesel-powered vehicles. While electric vehicles (EVs) are an excellent alternative for passenger cars, hydrogen fuel cells offer a more practical solution for heavy-duty transport, such as trucks, buses, ships, and even airplanes. Fuel cell electric vehicles (FCEVs) convert hydrogen into electricity, producing only water vapor as a byproduct, making them completely emission-free. Unlike battery-electric vehicles, which require long charging times and have weight limitations, hydrogen-powered vehicles can be refueled in minutes and offer longer ranges, making them ideal for long-haul transport. In maritime and aviation sectors, where battery technology still struggles to provide enough power for long distances, hydrogen-based fuels like ammonia and synthetic fuels are being developed. These advancements are crucial for reducing the environmental impact of global shipping and air travel,
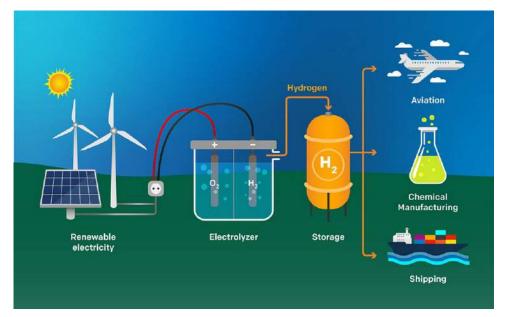
Fig. 2: Largest Green Hydrogen Project [2]

which currently rely on fossil fuels and contribute significantly to greenhouse gas emissions.

3. Energy Storage & Power Generation

One of the biggest challenges with renewable energy sources like solar and wind is their intermittency—they do not produce energy continuously. Green hydrogen serves as an energy carrier, enabling the storage of excess electricity generated during peak production periods for later use. Hydrogen can be stored in tanks, underground caverns, or pipelines and converted back into electricity using fuel cells or hydrogen turbines when needed. This makes it a key solution for grid stabilization, ensuring a steady power supply even when solar and wind generation is low [3]. Additionally, hydrogen-powered power plants can be integrated into existing energy systems, replacing fossil fuel-based power generation with clean and reliable alternatives.

Innovations & Global Efforts Towards Green Hydrogen

Green hydrogen is rapidly emerging as a key solution in the fight against climate change, and continuous innovations, government initiatives, and global collaborations are driving its expansion. Technological advancements are helping to reduce production costs and improve efficiency, while nations worldwide are implementing policies and investments to accelerate large-scale adoption. Below are the major developments shaping the future of green hydrogen.

1. Recent Technological Advancements

One of the biggest challenges for green hydrogen has been the high cost of production, primarily due to the expensive process of electrolysis, which requires significant electricity input. However, recent advancements in electrolyzer technology have drastically improved efficiency, making hydrogen production more cost-effective.

Next-generation electrolyzers: Researchers are developing solid oxide electrolyzers (SOECs) and anion exchange membrane (AEM) electrolyzers, which operate at higher efficiencies and lower costs compared to conventional alkaline or proton exchange membrane (PEM) electrolyzers. Cheaper catalysts: Traditional electrolyzers rely on expensive materials like platinum and iridium. New alternatives using nickel, iron, and cobalt-based catalysts are making green hydrogen production more affordable. Integration with renewables: Advanced smart grid technologies and AI-driven optimization are enabling better integration of electrolysis plants with solar and wind farms, reducing energy waste and maximizing hydrogen output. These

innovations are expected to significantly lower the cost of green hydrogen, making it more competitive with fossil fuel-based alternatives in the coming years.

2. Government Policies & Investments

Governments across the world are recognizing the potential of green hydrogen and have launched ambitious policies and funding programs to accelerate its adoption. Leading nations such as Germany, Japan, and the U.S. are investing billions in research, infrastructure, and hydrogen-powered industries.

Germany: As part of its National Hydrogen Strategy, Germany has committed €9 billion ($10 billion) to support green hydrogen projects, with a focus on industrial decarbonization and international partnerships. Japan: A pioneer in hydrogen fuel cell technology, Japan has set aggressive targets for hydrogen-powered transport and aims to develop a full-scale hydrogen economy by 2050. The country is also investing heavily in liquid hydrogen shipping to import hydrogen from Australia and the Middle East. United States: The U.S. government has introduced the Hydrogen Shot initiative, aiming to reduce the cost of clean hydrogen production by 80% to $1 per kilogram within the next decade. The Bipartisan Infrastructure Law has allocated billions for hydrogen hubs and electrolyzer production. Many other nations, including Australia, China, South Korea, and Saudi Arabia, are also developing hydrogen roadmaps and investing in large-scale production facilities, further accelerating global adoption.

3. Major International Collaborations & Projects

The shift towards a hydrogen-based economy requires global cooperation, and several international projects and alliances have been formed to support the development, trade, and infrastructure of green hydrogen. The European Hydrogen Backbone Initiative: A multinational project aiming to build a hydrogen pipeline network across Europe, ensuring the efficient transport of hydrogen between countries. The Hydrogen Council: A global coalition of leading energy, transport, and industrial companies working together to accelerate hydrogen deployment worldwide. NEOM Green Hydrogen Project (Saudi Arabia): One of the world's largest green hydrogen plants is being built in Saudi Arabia's NEOM city, designed to produce 650 tons of hydrogen per day, which will be exported globally. Australia-Germany Hydrogen Partnership: A joint effort where Australia produces green hydrogen using its vast renewable resources, and Germany imports it for industrial use.

Conclusion

Green hydrogen is emerging as a game-changer in the global shift toward sustainable energy. With its ability to replace fossil fuels in industries, revolutionize transportation, and provide efficient energy storage, it holds immense potential to combat climate change and reduce carbon emissions. Unlike conventional hydrogen production, which relies on fossil fuels, green hydrogen is generated using renewable energy sources, making it a truly clean and sustainable solution.

Despite its promising future, challenges such as high production costs, limited infrastructure, and efficiency concerns still need to be addressed. However, continuous advancements in electrolysis technology, government-backed policies, and international collaborations are accelerating its large-scale adoption. As more investments flow into research and development, the cost of green hydrogen is expected to decrease, making it a viable alternative for industries and energy markets worldwide.

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EMERGENCE OF 3D INTEGRATED CIRCUITS (3D-ICs)

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Abstract

As semiconductor technology approaches the physical and performance limitations of traditional 2D integrated circuits (ICs), the emergence of 3D Integrated Circuits (3D-ICs) has become a transformative innovation in modern electronics. By leveraging vertical stacking of multiple silicon layers, 3D-ICs enhance transistor density, improve performance, and significantly reduce power consumption. This breakthrough architecture addresses critical challenges such as interconnect delays and heat dissipation while enabling advancements in high-performance computing (HPC), artificial intelligence (AI), and the Internet of Things (IoT). This article delves into the technological developments, fabrication methodologies, key advantages, and future potential of 3D-ICs, shedding light on their impact across multiple industries and their role in shaping the next generation of semiconductor devices.

Introduction

Due to the quick progress towards semiconductors, there is a heightened need for high powered and compact efficient integrated circuits. Classical 2D Integrated Circuits (ICs) are now suffering from limitations in scaling of transistors, power consumption, and interconnect delays. The emergence of 3D Integrated Circuits (3D-ICs) aims to solve these problems. 3D Integrated Circuits provide a novel method to chip design by stacking silicon wafers, or dies on to each other. This form of vertical integration achieves higher component density while simultaneously improving performance and reducing latency. 3D-ICs have, and will continue being, a key stimulant in the evolution of electronic devices. One of the key things to note about 3D-ICs is that they enhance data transfer speeds while minimizing combustion energy. With such energy minimal device cooling systems would be easier to manage. In 2D systems, extended interconnects result in power loss and slower signal speeds. Unlike 2D systems, 3D-ICs utilizeThrough-Silicon Vias (TSVs) and other modern bonding methods to create more efficient interconnects between stacked components. These measures lower resistance, and energy usage while boosting signal speed and integrity. Why are such uncomplicated conveniences useful? Such measures are valuable for high performance computing (HPC) tasks, or artificial intelligence (AI) accelerators in data hubs.The increased use of 3D IC technology is impacting critical sectors including 5G telecoms, the IoT, and medical electronics. 3D ICs are perfect for edge computing, AI applications, and future wireless communication systems because of their ability to converge logic, memory, and sensors in a singular compact package. They also have enhanced performance, and the ability to 3D ICs allows for the creation of wearable devices, biomedical implants, and advanced imaging technologies that transform automation and healthcare. Despite the numerous benefits 3D IC's provide, there are challenges that pose as barriers to achieving mass adoption. Heat management is problematic due to the stacked layers of silicon, which leads to lower reliability and performance. High costs associated with fabrication, lack of sufficient production,

and unfabricated testing facilities are barriers for mass production. However, research into new materials and cooling technologies, alongside advanced manufacturing methods, are expected to make strides in 3D IC technology. The semiconductor industry is evolving, and 3D IC chip design represents one of the most significant changes.

Fabrication Techniques of 3D Integrated Circuits

The construction of 3D Integrated Circuits (3D-ICs) is performed by stacking several silicon wafers or dies vertically to achieve better performance and increased integration density. This enhances the dissipation of heat, interconnect technologies, and bonding techniques which ensures they are all operational[2]. Given below are the important techniques in regards to the fabrication of 3D-ICs:

1. Through Silicon Via (TSV) Technology

Through Silicon Via (TSV) technology is among the leading techniques used in interconnection of stacking layers in 3D-IC Mounting Architecture. TSVs are used for horizontally stacked Integrated Circuits (ICs) and they are vertical interconnections that go into the siliconed engineered layers. The task starts with Wafer Thinning, where silicon siliconed structures are reduced out to several micrometers to decrease the height of the arrangement. Then, small vias are drilled into the wafer with deep reactive ion etching (DRIE), insulated, and metal filler, where the vias are blasted away from the isolating cover, often applied as silicon dioxide, and replaced with conductive copper or tungsten. The last step is wafer bonding and stacking with TSVs, which makes it possible for direct electrical communication between the bonded layers. The use of TSVs improves data transfer rate, active power usage, and compact design with smaller interconnects. Unfortunately, the process is expensive and complicated, and there is thermal stress because expansion does not match the coefficient of thermal expansion (CTE).

2. Wafer-to-Wafer Bonding

In wafer-to-wafer bonding, entire wafers are stacked and then diced into individual 3D chips. This technique ensures alignment at the wafer level before cutting. Various bonding methods include direct bonding, which uses van der Waals forces and requires high temperatures for strong adhesion; adhesive bonding, which uses polymer-based adhesives for bonding at lower temperatures; and metal bonding (Cu-Cu, Al-Al), which uses metallic interconnects for high-conductivity bonding. The advantages of wafer-to-wafer bonding include high alignment accuracy and suitability for mass production of 3D-ICs. However, yield loss can occur if defects exist in any wafer layer, and precise wafer thinning and alignment are required.

3. Die-to-Die Bonding

In die-to-die bonding, individual pre-fabricated chips (dies) are stacked on top of each other and interconnected. Flip-chip bonding, which uses microbumps or solder balls to connect dies, and hybrid bonding, which combines direct metal bonding with oxide-to-oxide adhesion for better electrical performance, are common methods. This technique allows stacking of different chip technologies (heterogeneous integration) and reduces waste compared to wafer-to-wafer bonding. However, die-to-die bonding requires precise alignment for each individual die and takes longer compared to wafer-level bonding.

4. Monolithic 3D Integration

Monolithic 3D integration differs from TSV-based stacking by building multiple device layers on the same silicon wafer sequentially rather than stacking separate dies. The process involves fabricating the first layer of transistors, depositing an interlayer dielectric, and then growing the second layer of transistors using silicon epitaxy. Monolithic integration eliminates the need for TSVs, reducing fabrication complexity. It allows for ultra-dense integration with lower power consumption. However, high-temperature processing can damage lower layers, and manufacturing at large scales is challenging.

5. Interposer-Based 3D Packaging (2.5D-ICs)

In 2.5D-ICs, an interposer, a thin silicon substrate with built-in interconnects, acts as a bridge between multiple chips. This approach is considered a stepping stone between traditional 2D-ICs and fully stacked
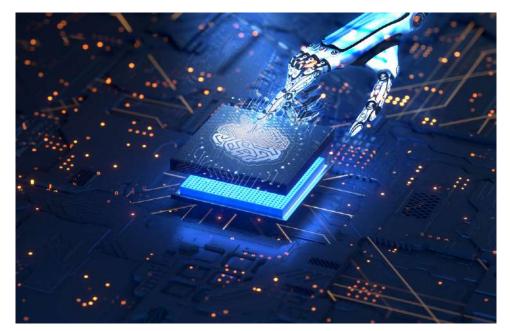
Fig. 1: 3D-ICS [1]

3D-ICs. The process involves fabricating a silicon or organic interposer with embedded interconnects, placing multiple dies onto the interposer, and connecting them using microbumps. The final chip assembly is then packaged and tested. Interposer-based packaging enables heterogeneous integration (combining different technologies like memory and logic chips) and has lower thermal issues compared to direct 3D stacking. However, it comes with increased design complexity and higher costs due to additional interposer fabrication.

Future Trends and Innovations in 3D-ICs

The future of 3D Integrated Circuits (3D-ICs) is poised for groundbreaking innovations that will redefine the landscape of electronics. As the need for faster processing, higher integration, and greater energy efficiency continues to grow, several exciting trends are emerging that promise to shape the development of next-generation 3D-ICs. These trends focus on addressing the current challenges in the industry while opening new possibilities in performance and technology.

- Advanced Cooling Solutions for Heat Dissipation

One of the most significant challenges in 3D-IC technology is heat management. The vertical stacking of multiple layers in 3D circuits can cause heat to accumulate, potentially leading to performance degradation and reliability issues. As devices become more powerful, finding effective cooling solutions is crucial. Innovative cooling methods are being developed to address these issues. One such solution involves microfluidic cooling, where small channels are embedded within the chips to circulate coolant, efficiently dissipating heat. Other approaches include advanced materials like diamond-like carbon coatings, known for their exceptional thermal conductivity, and the development of thermal vias, which are designed to transport heat away from critical layers. These cooling techniques are essential for ensuring that 3D-ICs can continue to operate at optimal performance levels without overheating.

- Hybrid Integration with Photonics and Quantum Computing

Another exciting frontier in 3D-IC technology is the hybrid integration of photonics and quantum computing. Photonic circuits, which use light rather than electrical signals to transmit data, offer the potential to greatly enhance the speed and reduce the power consumption of 3D-ICs. By incorporating photonic interconnects, these chips can achieve data transmission speeds that far surpass conventional electrical

connections. This innovation is especially crucial as data processing demands grow exponentially. Additionally, quantum computing, with its ability to solve complex problems much faster than classical computers, is being integrated with 3D-ICs. This fusion could lead to highly efficient computing systems capable of tackling challenges in fields such as artificial intelligence, cryptography, and simulations.

- AI-Driven Optimization in 3D-IC Design and Manufacturing

Artificial Intelligence (AI) is revolutionizing the design and manufacturing processes of 3D-ICs. With the increasing complexity of these circuits, AI tools are being used to optimize everything from circuit layout to interconnect design. AI algorithms can predict and resolve potential issues in the early stages of the design process, reducing costly revisions and improving overall yield rates. Additionally, AI plays a key role in automating and refining manufacturing processes, ensuring that each stage from wafer thinning to stacking is as efficient as possible. With AI's ability to analyze vast amounts of data, 3D-IC designs can continuously evolve to meet the demanding needs of next-generation electronic systems.

- Emerging Materials for Better Performance and Efficiency

The performance of 3D-ICs is largely determined by the materials used in their construction. To keep up with the growing demands for faster, more efficient circuits, researchers are turning to new materials that offer superior properties compared to traditional silicon. Graphene and carbon nanotubes, for example, have shown great promise due to their excellent electrical conductivity and thermal properties. These materials could help overcome some of the limitations of silicon, particularly in terms of heat dissipation and processing speed. Additionally, advanced dielectrics are being explored to enhance the insulating layers between stacked chips, reducing power loss and improving overall efficiency. Flexible materials are also gaining attention, offering the possibility of integrating 3D-ICs into a wider range of applications, including wearable electronics and flexible displays.

Conclusion

In conclusion, the future of 3D-IC technology is incredibly promising, driven by continuous advancements in key areas such as cooling solutions, hybrid integration with emerging technologies, AI-enhanced design processes, and the development of novel materials. These innovations aim to tackle current challenges such as heat dissipation, performance limitations, and energy efficiency, paving the way for even more powerful and compact electronic devices. As the demand for faster, smarter, and more energy-efficient systems grows, 3D-ICs will play a critical role in shaping the future of electronics, offering new opportunities across industries such as computing, communications, and beyond. The ongoing research and breakthroughs in these areas will ensure that 3D-IC technology remains at the forefront of technological advancement in the years to come.

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NEUROMORPHIC COMPUTING

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Abstract

Neuromorphic computing represents a paradigm shift in electronic system design, inspired by the structure and functionality of biological neural networks[3]. This approach seeks to bridge the gap between conventional von Neumann architectures and highly parallel, energy-efficient neural computation. By leveraging Spiking Neural Networks (SNNs) and neuromorphic processors, this technology aims to enhance the computational efficiency, adaptability, and real-time processing of AI-driven systems. This paper explores the fundamental principles of neuromorphic computing, its architectures, applications, challenges, and future research directions.

Introduction

The ever-growing demand for intelligent computing solutions has led to the emergence of neuromorphic computing, an approach inspired by the biological brain[1]. Unlike conventional computers that operate sequentially, neuromorphic systems process information in parallel using specialized circuits that mimic neurons and synapses. This technique improves real-time responsiveness and energy efficiency, making it suitable for applications in robotics, AI, and embedded systems. Neuromorphic computing employs event-driven processing, reducing unnecessary computations, and enables adaptive learning through plasticity mechanisms such as Spike-Timing-Dependent Plasticity (STDP) and Hebbian learning.

Architectures and Key Components

Neuromorphic computing relies on a specialized design that replicates the brain's neural architecture, enabling unprecedented capabilities in electronics and communication. Let's break down its architectures and key components:

1. Neuromorphic Architectures

Neuromorphic systems are built to mirror the brain's distributed and parallel processing capabilities. These architectures include:

Spiking Neural Networks (SNNs): Unlike traditional artificial neural networks, SNNs process information through spikes—brief bursts of electrical signals, similar to the way neurons communicate[1]. SNNs enable faster, more efficient computation, particularly suited for real-time tasks like speech recognition and sensory data analysis.

Event-Driven Processing: Neuromorphic systems process only relevant inputs, ignoring redundant or irrelevant data. This event-driven nature ensures energy-efficient operation, especially for communication networks that deal with large volumes of dynamic data.

Hierarchical Designs: Neuromorphic architectures use hierarchical layers to handle different aspects of

computation. For example, one layer might

2. Key Components

Neuromorphic systems are composed of specialized hardware and software components that work together seamlessly:

Neuromorphic Chips:

- • Analog Chips: Simulate the continuous[2], non-digital behavior of neurons, making them highly energy- efficient for tasks like sensory data processing. •
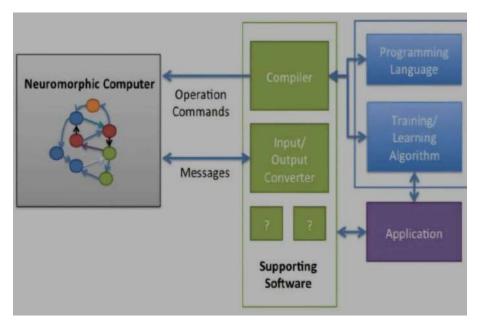- Digital Chips: Use binary signals to mimic neural activity, offering compatibility with traditional systems.

Fig. 1: A Potential neuromorphic architecture from the computer science perspectives[3]

Memristors:

These are resistive memory devices that mimic synapses by storing information in the form of electrical resistance. Memristors allow neuromorphic systems to learn and adapt, making them essential for applications like adaptive signal processing and edge computing in communication systems.

Synaptic Arrays: These interconnected units replicate the connections between neurons. Synaptic arrays enable the dynamic reconfiguration of neural networks[3], essential for adaptive electronics and self-learning systems.

Event-Based Sensors:

Sensors like neuromorphic vision and audio sensors process data in real time, outputting only relevant information. These sensors are ideal for applications in real-time communication and electronics, where speed and accuracy are crucial

Learning Algorithms:

• Hebbian Learning: Based on the "fire together, wire together" principle, this algorithm strengthens connections between frequently activated neurons. • Spike-Timing-Dependent Plasticity (STDP): Adjusts synaptic strength based on the timing of spikes, enabling self-learning capabilities.

Research Trends and Future Prospects

- **Energy Efficiency**: Advancing low-power computing architectures to minimize energy consumption while maximizing performance.
- **Integration with AI**: Developing neuromorphic processors for enhanced AI computation, improving real-time decision-making and adaptability[1].
- **New Materials**: Exploring the use of novel materials such as phase-change memory and carbon nanotubes to create more efficient neuromorphic systems.
- **Scalability**: Addressing challenges in scaling up neuromorphic networks while maintaining high efficiency and robustness.
- **Brain-Computer Interfaces (BCIs)**: Investigating neuromorphic computing for direct human-machine interactions, including assistive technologies and neural prosthetics.
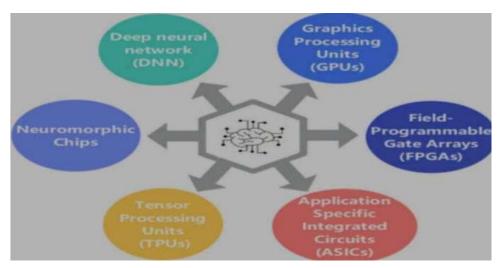

Fig. 2: Research trends and future prospects[3]

Challenges in Neuromorphic Computing

- **Energy Constraints**: Balancing power efficiency while maintaining computational effectiveness in large-scale neuromorphic systems.
- **Integration with Traditional Systems**: Ensuring compatibility with existing digital architectures and software frameworks.
- **Hardware Complexity**: Developing reliable[2], scalable neuromorphic chips with high-speed processing capabilities.
- **Programming Models**: Designing efficient frameworks to program and train neuromorphic networks for diverse applications.

Applications of Neuromorphic Computing

- **AI and Robotics**: Enhancing autonomous systems with real-time decision-making and adaptive learning capabilities.
- **Healthcare and Biomedical Devices**: Improving diagnostic tools and wearable health monitoring systems.

- **Cybersecurity**: Implementing real-time anomaly detection and AI-driven security mechanisms.
- **Edge Computing**: Deploying low-power, high-efficiency processors for IoT and embedded systems.

Conclusion

Neuromorphic computing holds tremendous potential in revolutionizing computational paradigms by mimicking biological intelligence. With advances in AI, materials science, and chip design, this field is poised to drive future technological innovations. Overcoming current challenges in hardware development, programming models, and scalability will be crucial for its widespread adoption. As research progresses, neuromorphic computing is set to redefine AI applications, making them more efficient, adaptive, and human-like in processing capabilities.

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