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Hybrid Deep Learning Techniques for Plant Pathogen and Disease Diagnosis using the Internet of Bio-Nano Things

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Abstract

Objective

The primary goal of this study is to address the security concerns associated with the practical application of Bio Cyber Interfaces (BCIs) in the context of the Internet of Bio-Nano Things (IoBNT). Specifically, the objective is to accurately classify abnormal patterns in BCI traffic to enhance the overall security of BCIs connected to the Internet (5G).

Materials and Methods

This section outlines the materials and methods employed in the study. It encompasses the use of a hybrid ensemble comprising Convolutional Neural Networks and Long Short-Term Memory (CNN + LSTM) for flexible and scalable feature design. The study involves the utilization of current Machine Learning (ML) anomaly detection techniques and explores the complexities of parameters and correlations among BCI traffic parameters. Additionally, the creation and validation of a dataset are discussed.

Results

The results section presents the findings of the study, focusing on the performance of the hybrid ensemble Deep Learning (DL) model (CNN + LSTM). It includes details on the accuracy achieved, comparisons with other DL architectures, and insights gained from rigorous validation using singular and multi-dimensional models on the generated dataset.

Conclusions

The conclusion summarizes the key implications and contributions of the study. It discusses the significance of the hybrid ensemble (CNN + LSTM) in achieving a high accuracy of approximately 94.6% in classifying abnormal BCI traffic. Furthermore, it emphasizes the importance of addressing security concerns associated with BCIs connected to the Internet (5G) for their practical application in the context of IoBNT.

Keywords: Internet of Bio-Nano Things, Plant Pathogens, Deep Learning, Bio Cyber Interface, CNN, LSTM.

Paper Type: Research Paper.

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Introduction

The imperative to augment agricultural productivity and guarantee the security of the food chain is escalating in response to the burgeoning global populace. The consensus among scholars is that plant diseases significantly impact global agricultural productivity. Various plant pathogens, such as viruses, fungi, and bacteria, are perceived as detrimental external factors that can lead to diverse plant infections and diminish agricultural productivity (Pérez Vázquez et al. 2018). The rapid dissemination, increasing prevalence, and escalating severity of these threats have engendered significant concern regarding the global food supply. The abovementioned phenomenon results in significant devastation as it negatively impacts agricultural produce, which serves as a primary source of sustenance for the disproportionately large population, particularly in underprivileged emerging regions. Additionally, according to the Food and Agriculture Organization, it is estimated that plant diseases result in an annual economic loss of approximately \$225 billion to the global economy. In comparison, aggressive insects cause losses of at least

$75 billion. In the province of Georgia, approximately 829 million dollars has been projected for the economic impact of plant pathogens and their management in 2020 (Johnson et al. 2021).

The primary method employed for identifying plant pathogens and the subsequent diagnosis of symptoms and diseases is visual observation, which typically requires the expertise of an experienced plant grower or biologist (Rawat et al. 2022). Nevertheless, its efficacy is limited in the early stages of infection when plants do not exhibit any visible symptoms, making it difficult to detect the presence of pathogens. The IoBNT is a developing concept founded upon recent advancements in molecular interaction, artificial biology, and the IoT. Molecular communication involves establishing biological systems that can be utilized collaboratively for moving transformed cells towards specific targets and precisely delivering necessary chemical enzymes. Moreover, integrating a biological network with internet access via BCI enables the external control, coordination, and regulation of enzymes in specific regions, thereby creating significant prospects for innovative medical devices in the future (Zafar et al. 2021).

Ongoing endeavors are underway to comprehend the complexities of information dissemination in biological networks through simulations, detailed mathematical models, or laboratory experiments. However, the practical verification of IoBNT has been notably achieved through the advancement of bio-electric interfaces, which enable communication between biological networks and the Internet (Chude-Okonkwo et al. 2016). Various technologies, including digital piercings, hydro-gel conductors, and chemo-electro transmission units, have been designed and extensively studied to establish a connection between the human body and the Internet. These technologies have shown significant progress and promise. The continuous efforts in managing and releasing bio-chemicals within the human body through BCI on the Internet have given rise to significant security and privacy concerns within the context of the IoBNT paradigm (Bakhshi and Shahid 2019). Security vulnerabilities in the context of IoBNT-based drug delivery can give rise to various issues, such as susceptibility to exploitation by evil entities. These entities may manipulate the system to cause inappropriate doses or enzyme discharge, thereby affecting the normal functioning of cells and the general functioning of the human body. They may also employ countermeasures, such as producing insect repellents, to counteract the intended effects of the administered drugs. These activities can be categorized under the umbrella term of bioterrorism (Sicari et al. 2019). The IoBNT framework's susceptibility to malicious assaults, coupled with its significant potential benefits, necessitates the implementation of security primitives through careful design, installation, and thorough testing. This approach is crucial to guarantee the framework's future flexibility and instill the public's trust in this technology. To achieve this objective, the current study examined and categorized the security disturbances to IoBNT resulting from outside threat vectors. A proposed holistic security structure for the

BCI based on the IoBNT is discussed, considering the current state of the art (El-Fatyany et al. 2020). A parameter monitoring scheme uses ML techniques to detect and verify authentic (external) connection queries and usage. Furthermore, the design employs a transparent and ongoing verification mechanism, which enhances security by providing an additional layer of protection to facilitate genuine usage. The security model under consideration is evaluated through comprehensive simulations conducted on generated data to analyze time-consuming and scalability considerations. The rest of the paper has been organized as follows: Section 2 provides the research background; Section 3 presents hybrid Deep Learning Techniques for plant pathogen detection using the IoBNT; Section 4 provides the results and discussion. Finally, the conclusion, limitations, and future work have been given in section 5.

Background of the Work

The rapid incorporation of cutting-edge technology has profoundly transformed agricultural methodologies, providing novel approaches to improve the well-being and output of crops. Within this framework, the IoBNT paradigm can potentially bring about significant changes. It does this by integrating the capabilities of the IoT with bio-nano communication. The resulting amalgamation enables accurate monitoring and diagnosis within the field of agriculture. This literature review examines the latest advancements in plant pathogen and disease detection, specifically emphasizing the creative use of Hybrid DL Techniques within the IoBNT framework.

Balasubramaniam et al. (2023) propose molecular machine learning via communications for Biological AI. Implementation integrates molecular communication with ML methods for biological applications. A molecular ML framework with promising bioinformatics findings is produced. Leveraging communication processes in molecular systems for AI has benefits; however, integrating these technologies in biological contexts may be difficult.

Mishra et al. (2023) describe bioinspired sustainable sensing technology improvements. The technique explores bioinspired sensing technologies for sustainability. Implementation involves creating biologically inspired sensors. Sustainable sensing technologies with bioinspired designs are reviewed. Eco-friendly sensing technologies provide benefits; however, bioinspired sensor scalability and repeatability may be issues. A distributed routing and self-balancing system for Medical IoNT was introduced by Gulec (2023). Medical IoNT communication and load management are managed by creating an algorithm. The implementation boosts IoNT network efficiency. A medical IoNT self-balancing algorithm is produced. Algorithm complexity may reduce network performance. Civas et al. (2023) study graphene and similar materials for The Internet of Bio-Nano Things. The approach investigates graphene in bio-nano communication systems. Materials are characterized and tested in bio-nano settings. The outcome suggests graphene uses in bio-nano communication. Scalability and cost issues may arise; however, material diversity is advantageous. Nikhat and Yusuf (2020) assessed the IoBNT current and future conditions. The approach reviews IoNT technologies in detail. The implementation summarizes IoNT's current and future potential. Knowledge consolidation is beneficial, while IoNT technology advancement may be negative.

For the Internet of Bio-Nano Things, Zafar et al. (2021a) discuss BCI technologies and security challenges. Reviewing BCI technologies for bio-nano communication is the technique. The implementation generates a comprehensive examination of security issues and technology. Understanding security concerns is beneficial, but growing security risks may be a drawback. Particle Swarm Optimization (PSO) and Artificial Neural Networks (ANN)-based parameter profiling are suggested by Zafar et al. (2021b) for bio-cyber interface security for the Internet of Bio-Nano Things. Security parameters are optimized using PSO and ANN. The implementation improves bio-nano communication security. A better security framework is produced. Advantages include increased security. However, processing costs may be a problem.

Chaudhary and Chaudhary (2022) propose IoNT-inspired intelligent plant pathogen-diagnostic biosensors. Biosensors inspired by IoNT are used to diagnose plant pathogens. The implementation uses sophisticated biosensors to identify pathogens. A unique plant health biosensing method has been developed. Although sensor calibration and environmental conditions may be issues, pathogen identification is exact. For IoBNT bioluminescent interface security, Bakhshi and Zafar (2023) suggest hybrid DL. The approach uses DL to secure bioluminescent interfaces. The implementation shows better bio-nano communication security. Hybrid DL produces a safe architecture. Security is good, but resource-intensive calculations may be a problem (Table 1).

Materials and Methods

Hybrid DL Techniques for Plant Pathogen and Disease Diagnosis using the IoBNT: Incorporating Hybrid DL Techniques within the context of the IoBNT signifies an advanced methodology for transforming the field of plant pathogen and disease identification in the agricultural sector. Integrating sophisticated DL techniques with the accuracy of bio-nano communication shows great potential in effectively resolving the complexities related to timely and precise evaluation of crop well-being. Integrating IoT with bio-nano communication provides a comprehensive approach to continuous surveillance and diagnosis.

Table 1. Related works

Reference	Proposed Methodology	Implementation	Output with Result Value	Advantages	Disadvantages
(Balasubramaniam et al. 2023)	Realizing molecular ML through communications for Biological AI.	Integration of molecular communication techniques with ML algorithms for biological applications.	Framework for molecular machine learning; promising results in bioinformatics tasks.	Leveraging communication mechanisms in molecular systems for AI.	The complexity of integrating these technologies in biological environments.
(Mishra et al. 2023)	Recent advances in bioinspired sustainable sensing technologies.	Exploration of bioinspired sensing technologies for sustainable applications.	Development of sensors inspired by biological systems; review of sustainable sensing technologies.	Eco-friendly sensing solutions.	Scalability and reproducibility of bioinspired sensors.
(Gulec 2023)	Distributed routing and self-balancing algorithm for Medical IoNT.	Designing an algorithm to manage communication and balance the load in medical IoNT.	Improved efficiency in IoNT networks; self-balancing algorithm for medical IoNT.	Enhanced network performance.	Algorithm complexity.
(Civas et al. 2023)	Graphene and related materials for the Internet of Bio-Nano Things.	Exploration of the use of graphene in bio-nano communication systems.	Material characterization and testing in bio-nano environments;	Material versatility.	Scalability and cost considerations.
(Nikhat and Yusuf 2020)	The Internet of Nano Things (IoNT) existing state and future Prospects.	Comprehensive review of IoNT technologies.	Overview of the current state of IoNT and future possibilities.	Knowledge consolidation.	Rapid evolution of IoNT technologies.
(Zafar et al. 2021a)	A systematic review of bio-cyber interface technologies and security issues for the Internet of Bio-Nano Things.	Review of bio-cyber interface technologies in the context of bio-nano communication.	Systematic review highlighting security challenges and technologies.	Comprehensive overview of security issues.	Evolving security threats.
(Zafar et al. 2021b)	Securing bio-cyber interface for the Internet of Bio-Nano Things using particle swarm optimization and artificial neural networks-based parameter profiling.	Optimizing security parameters using particle swarm optimization and artificial neural networks.	Enhanced security for bio-nano communication; an advanced security framework.	Advanced security measures.	Computational overhead.
(Chaudhary and Chaudhary, 2022)	A paradigm of Internet-of-Nano-Things inspired intelligent plant pathogen-diagnostic biosensors.	Development of biosensors inspired by IoBNT for plant pathogen diagnosis.	Intelligent biosensors for accurate pathogen detection; a novel biosensing approach for plant health.	Precise pathogen diagnosis.	Sensor calibration and environmental factors.
(Bakhshi and Zafar 2023)	Hybrid Deep Learning Techniques for Securing Bioluminescent Interfaces in Internet of Bio Nano Things.	Combining deep learning techniques for enhanced security in bioluminescent interfaces.	Improved security measures for bio-nano communication; a secure framework using hybrid deep learning.	Robust security.	Resource-intensive computations.

Integrating DL algorithms with BCI facilitates the development of intelligent devices that can provide prompt, precise, and data-centric analyses about the well-being of plants. This merger of transformational nature contributes to advancing our comprehension of crop illnesses and establishes a foundation for proactive and focused treatments. Consequently, it facilitates the emergence of a novel age in agriculture known as precision agriculture, which has the potential to raise crop yields and promote sustainability substantially.

Cloud-IoBNT, a recently established service, offers a cost-free web-based solution that streamlines the installation process of sensors situated in distant locations, allowing for easy integration and operation. Technical advancements have facilitated the accessibility of farming, since farmers have adopted novel practices that have significantly improved agricultural yields. The IoBNTs comprise a network of interconnected sensors, robots, mobile devices, and drones that operate autonomously or with little human intervention. These devices collaborate to perform various tasks and collect data, improving efficiency and precision. AI technologies are used in the domain of "smart farming" to effectively observe and evaluate the environmental conditions of agricultural land, enabling informed decision-making on optimal crop choice and planting strategies. These judgments are based on several aspects, including but not limited to soil composition, weather predictions, and water accessibility.

To support the 5G communication system, a straightforward channel is established to connect devices for seamless data interactions, ensuring minimal traffic congestion, data loss, and latency. This efficient approach significantly reduces the expenditure of time, resources, and finances. Regarding data transfer rates, it is anticipated that 5G technology would exhibit speeds that are potentially one hundred times greater than those seen in both 4G and 4G LTE networks. Potential applications of 5G in plant disease detection include a range of technologies, including Unmanned Aerial Vehicles (UAV), predictive maintenance, virtual consultation, continuous surveillance, AI-powered robots, Augmented and Virtual Reality (AR/VR), cloud archives, data analysis, and other related advancements (Chow et al. 2017). 5G technology facilitates the streamlined establishment, monitoring, and management of an extensive network, including IoBNTs devices and plant pathogens. Figure 1 shows the plant pathogen detection using hybrid DL techniques. Integrating large quantities of information from multiple sources will be advantageous in agriculture with the implementation of 5G technology. A large-scale farm's temperature and nutritional data are sent to a centralized hub. The many sensors' data do not warrant the cost and intricacy associated with 5G broadband connectivity. The potential bandwidth may align with that of 5G mobile broadband bandwidth if nodes are gathered in clusters of optimal size. UAVs outfitted with sensory devices and multispectral imaging cameras are deployed to gather data while traversing agricultural fields. Subsequently, this data is used by computer systems executing DL algorithms to evaluate and identify issues affecting plant health.

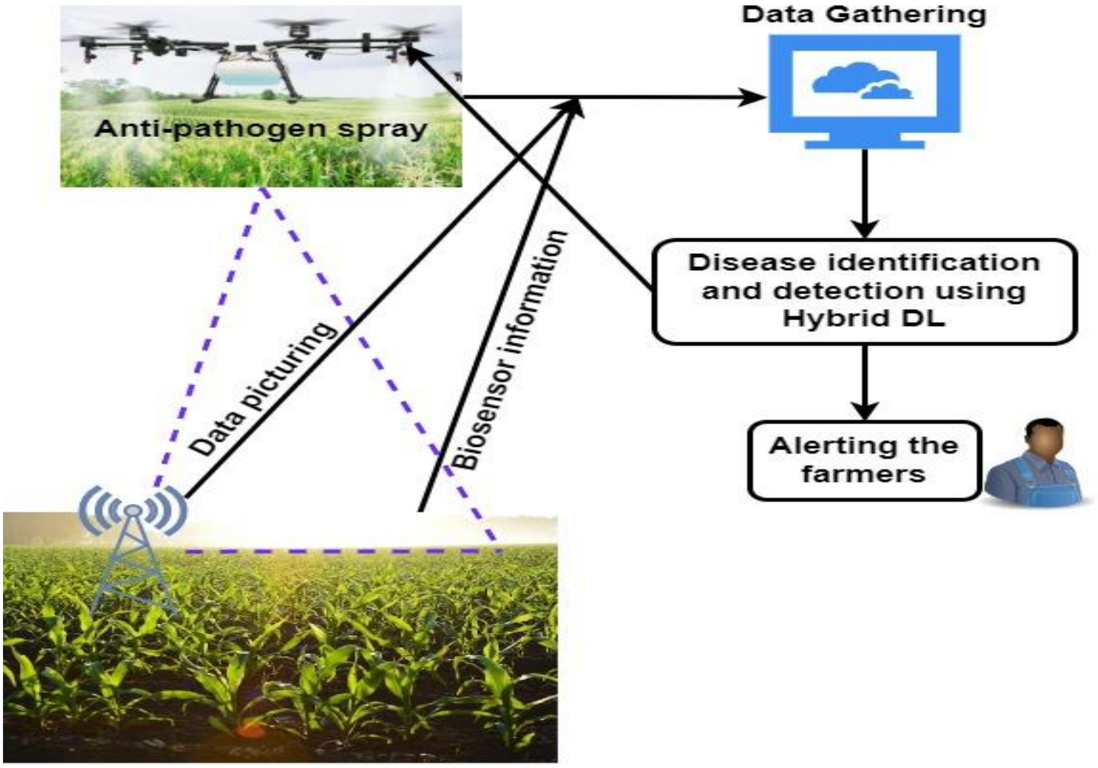

Figure 1. Plant Pathogen Detection using Hybrid DL Techniques

A growing number of agricultural practitioners are increasingly dependent on UAVs, also known as drones, to monitor their crops. Using drones instead of deploying tractors over fields offers a cost-effective way of evaluating damaged crops and other related aspects. Drones can gather and send video footage with enhanced quality and increased efficiency due to the use of 5G technology, which enables the handling of substantial volumes of data. Affected plants often exhibit distinct categorization compared to normal plants. Integrating IoBNT-integrated biosensors with AI, drones, 5G connection, and hybrid DL (CNN+LSTM) allows a straightforward acquisition of this data and detects abnormal BCI traffic (Alkishri, W., 2023).

Figure 2 depicts the hybrid DL technique (CNN+LSTM) for plant pathogen detection. It includes the following steps:

1. Data Collection: Acquire bio-cyber data, including biological signals or information obtained from nano-scale sensors that monitor the well-being of plants.
2. Data Preprocessing: The acquired data should be pre-processed to assure consistency and eliminate any noise present. In the context of biological signals, the process

may include many techniques, such as signal filtering, normalization, or transformation.

3. Utilization of Convolutional Neural Network (CNN) for Spatial Feature Extraction: In this study, a CNN is employed to extract spatial features from photographs or other spatial data about plant health. CNN can acquire hierarchical representations, therefore collecting significant patterns and characteristics that are pertinent to the task of pathogen identification.
4. Temporal Modeling Utilizing Long Short-Term Memory Networks (LSTMs): Incorporate LSTMs to effectively capture temporal relationships present in sequential data, specifically focusing on time-series information about plant health changes. LSTM models are particularly suitable for acquiring and analyzing temporal patterns, making them very efficient in capturing the dynamic characteristics associated with the health of plants.
5. The fusion of spatial and temporal characteristics involves integrating the data extracted by the CNN and LSTM layers to provide a unified representation. The fusion technique used in this study effectively incorporates the data's geographical and temporal dimensions, hence improving the model's capacity to identify intricate patterns linked to the presence of pathogens.
6. BCI: The incorporation of bio-cyber data into the model is referred to as Bio-Cyber Interfacing (BCI). This may include integrating biological signals or data from nano-scale sensors as supplementary input characteristics.
7. Training: The hybrid CNN+LSTM model is trained using a labelled dataset containing information about plant pathogens' presence or absence.

The objective is to optimize the model's parameters to minimize an appropriate loss function, such as cross-entropy.

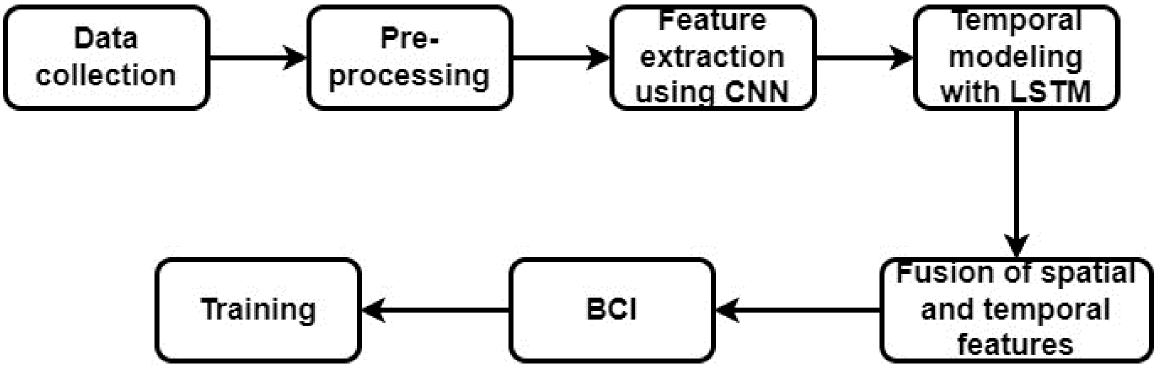

Figure 2. Hybrid DL Technique (CNN+LSTM) for Plant Pathogen Detection

The proposed technique in Algorithm 1 integrates spatial and temporal variables obtained from CNN and LSTM models. Furthermore, it incorporates supplementary data from BCI to enhance the detection capabilities of the model for identifying plant pathogens. Modifications and enhancements may be necessary depending on the data's unique attributes and the application's particular needs.

Algorithm 1: Hybrid CNN+LSTM Model with BCI

```
def hybrid_model_with_bci(X_spatial, X_temporal, X_bci):
    # CNN for spatial feature extraction
    features_cnn = CNN(X_spatial)
    # LSTM for temporal modeling
    features_lstm = LSTM(X_temporal)
    # Concatenate features with BCI data
    features_fusion = concatenate([features_cnn, features_lstm, X_bci], axis = −1)
    # Fully connected layer for classification
    output = Dense(num_classes, activation = 'softmax')(features_fusion)
    model = Model(inputs = [X_spatial, X_temporal, X_bci], outputs = output)
    return model
# Compile and train the model
model = hybrid_model_with_bci(X_spatial_train, X_temporal_train, X_bci_train)
model.compile(optimizer = 'adam', loss = 'categorical_crossentropy', metrics
        = ['accuracy'])
model.fit([X_spatial_train, X_temporal_train, X_bci_train], y_train, epochs
        = num_epochs, batch_size = batch_size)
```

Results and Discussion

The evaluation of a plant pathogen detection model in binary classification, where predictions are categorized as either positive or negative, often involves the use of the terms True Positive (TP), False Positive (FP), True Negative (TN), and False Negative (FN). The terms are calculated using confusion matrix and identified datas. The following equations denote the measures of accuracy, precision, and recall concerning the previously mentioned terms:

$$Accuracy = TP + TN/(FP + FN + TP + TN) \tag{1a}$$

$$Precision = TP/(FP + TP) \tag{1b}$$

$$Recall = TP/(FN + TP) \tag{1c}$$

These metrics provide a thorough assessment of the performance of the plant pathogen detection model. Accuracy is an assessment that evaluates the general correctness of a model's predictions. Precision, on the other hand, emphasizes the accuracy of positive predictions. Recall, however, prioritizes the ability to capture all real positive occurrences. It is important to consider the precise contextual circumstances of the issue at hand and the inherent compromises between these metrics, following the stipulated demands of the application. The performance of the proposed hybrid DL (CNN+LSTM) has been compared with other DL algorithms like CNN, LSTM, Gated Recurrent Unit (GRU), and CNN+GRU in terms of accuracy, precision, and recall for 10 epochs.

Figure 3 displays the validation accuracy (%) of several DL algorithms used for plant pathogen identification using IoBNT, recorded throughout ten epochs. During the first epoch, the CNN demonstrates a 79.5% accuracy, surpassing the performance of the LSTM model, which achieves 72.5% accuracy, and the GRU model, which reaches 73.4% accuracy. As the epochs advance, the CNN steadily improves its accuracy, ultimately achieving a notable 91.8% accuracy rate by the ninth epoch. The LSTM and GRU models demonstrate consistent albeit somewhat gradual improvements in accuracy, reaching 82.6% and 81.5%, respectively, after the tenth epoch. By the tenth epoch, the integration of CNN and GRU yields an accuracy of 88%.

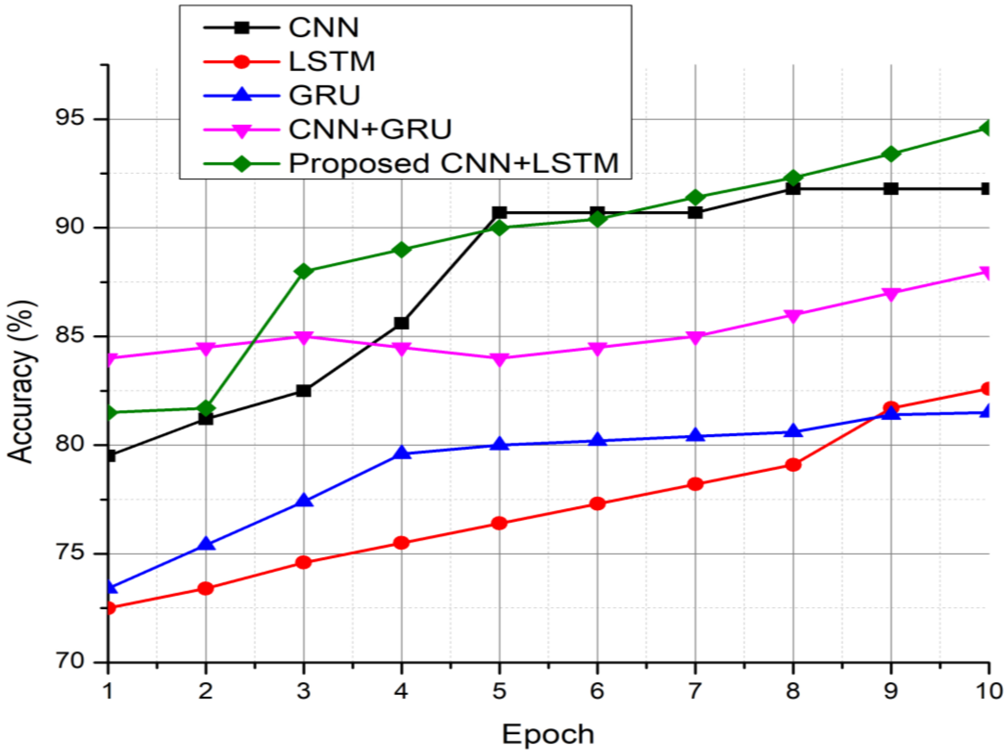

Figure 3. Validation Accuracy (%) of Various DL Algorithms for Plant Pathogen Detection using IoBNT

In contrast, the suggested model, which combines CNN and LSTM, outperforms the former by achieving an astounding accuracy of 94.6%. The findings indicate that the CNN+LSTM model, as suggested, exhibits superior performance compared to individual DL algorithms and their combinations in the context of plant pathogen identification. This underscores the efficacy of the combined CNN and LSTM architecture in improving accuracy throughout several training epochs. Figure 4 displays the precision values (%) of several DL algorithms used to identify plant pathogens using IoBNT. The results are recorded during ten epochs. During the first epoch, the CNN exhibits an accuracy rate of 87.2%, surpassing the performance of the LSTM model (68%), the GRU model (70%), the combined CNN and GRU model (78%), and the suggested combined CNN and LSTM model (80.2%). As the training process advances, the accuracy of all models often increases. In the ninth epoch, the CNN demonstrates a notable level of precision, reaching 91.1%.

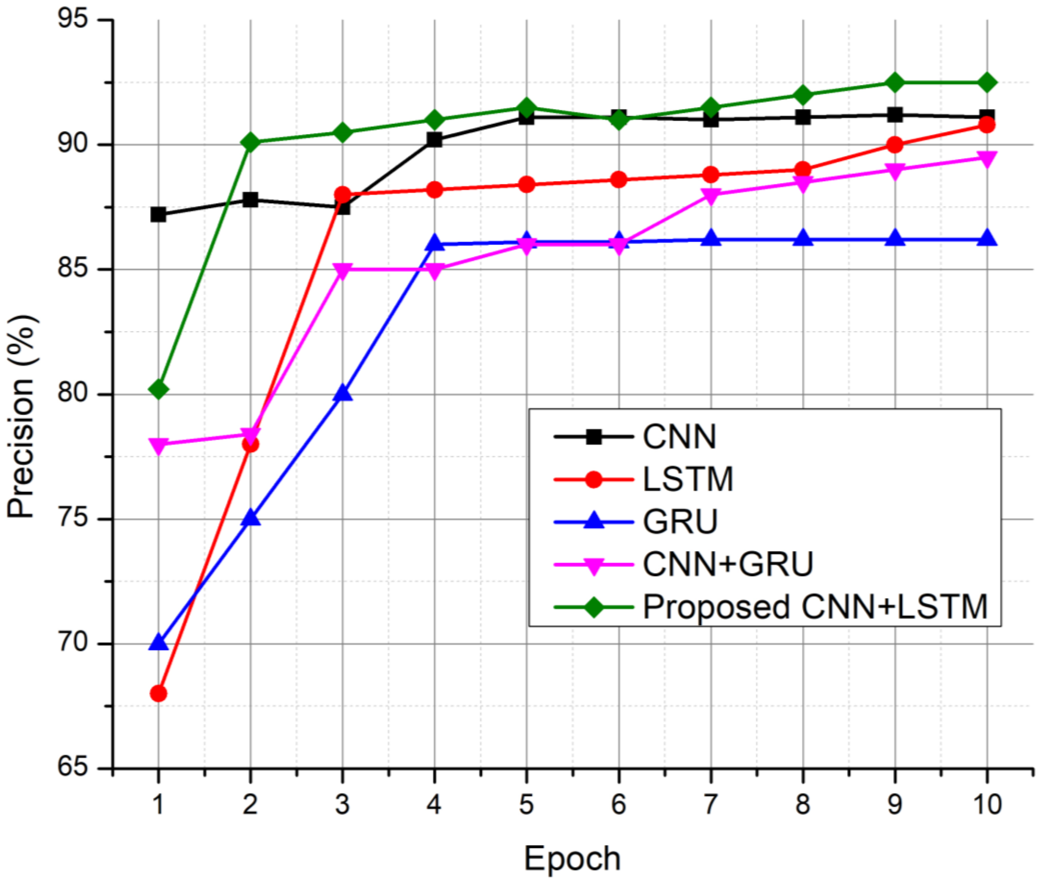

Figure 4. Precision (%) of Various DL Algorithms for Plant Pathogen Detection using IoBNT

On the other hand, the LSTM, GRU, and the combined CNN and GRU model acquire precision rates of 90.8%, 86.2%, and 89.5%, respectively. The proposed CNN+LSTM model has remarkable performance superiority over other models, with a precision rate of 92.5% for the tenth epoch. This finding suggests that the combined use of CNN and LSTM architecture is successful in attaining a superior level of precision in identifying plant pathogens, as compared to using other DL models. Figure 5 presents the recall (%) values for several DL methods in the context of plant pathogen detection using IoBNT throughout ten epochs. During the first epoch, the CNN demonstrates a recall rate of 85%, surpassing the LSTM model with a recall rate of 80.4%, the GRU model with a recall rate of 76.1%, the combined CNN and GRU model with a recall rate of 75%, and the suggested combined CNN and LSTM model with a recall rate of 88.5%. As the training process advances, the recall values for all models typically exhibit an upward trend. In the ninth epoch, the CNN demonstrates a recall rate of 89%. On the other hand, LSTM, GRU, and the combination of CNN and GRU acquire recall rates of 90.2%, 89%, and

82%, respectively. Significantly, the CNN+LSTM model exhibits steady and notable recall performance, achieving 91% by the ninth epoch. This finding implies that the use of CNN+LSTM has notable efficacy in attaining a substantial recall rate for the detection of plant pathogens, surpassing the performance of individual models and their combinations.

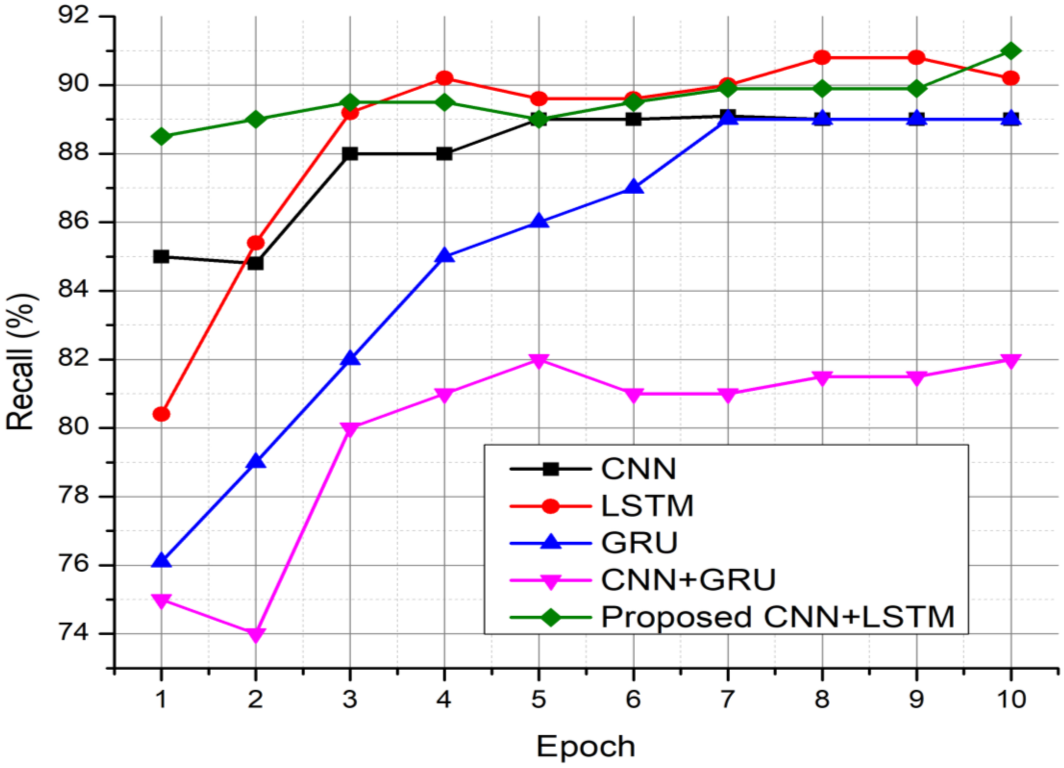

Figure 5. Recall (%) of Various DL Algorithms for Plant Pathogen Detection using IoBNT

Conclusion: The convergence of the biological and digital domains of the Internet is made possible by using a technologically sophisticated apparatus referred to as the BCI. The actual implementation of BCIs raises substantial apprehensions about their security. This is because integrating BCIs with the Internet, particularly via the utilization of 5G technology, exposes their interfaces to possible external vulnerabilities. It is essential to precisely categorize atypical patterns in BCI communication to tackle this issue. To accomplish this goal, the present study investigates the application of a hybrid ensemble comprising CNN + LSTM. This ensemble allows adaptable and expandable feature design to differentiate between typical and anomalous BCI traffic. By subjecting the created dataset to thorough validation using solitary and multi-dimensional models, our hybrid ensemble DL approach, specifically combining CNN and LSTM, demonstrated a remarkable accuracy of 94.6%. This performance surpassed that of existing DL architectures and allows effective plant pathogen detection. Cost associated with implementing the same will vary place to place and will have slight increase from the value of traditional one.

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شاپا چاپی: ۲۲۲۸-۶۷۰۵ شاپا الکترونیکی: ۲۲۲۸-۶۵۰۰

تکنیک‌های یادگیری عمیق ترکیبی برای تشخیص بیماری‌زاهای گیاهی و بیماری با استفاده از اینترنت اشیاء زیست نانو

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چکیده

هدف: هدف اصلی این مطالعه پرداختن به نگرانی‌های امنیتی مرتبط با کاربرد عملی رابطهای سایبری زیستی (BCIs) در زمینه اینترنت اشیاء زیست نانو (IoBNT) است. به طور خاص، هدف طبقه‌بندی دقیق الگوهای غیرعادی در ترافیک BCI برای افزایش امنیت کلی BCIهای متصل به اینترنت (5G) است.

مواد و روش‌ها: این بخش به تشریح مواد و روش های به کار رفته در مطالعه می‌پردازد. این شامل استفاده از یک مجموعه ترکیبی متشکل از شبکه‌های عصبی کانولوشن و حافظه کوتاه‌مدت بلند (CNN + LSTM) برای طراحی ویژگی‌های انعطاف‌پذیر و مقیاس‌پذیر است. این مطالعه شامل استفاده از تکنیک‌های تشخیص ناهنجاری یادگیری ماشینی (ML) است و پیچیدگی‌های پارامترها و همبستگی‌های بین پارامترهای ترافیک BCI را بررسی می‌کند. علاوه بر این، ایجاد و اعتبار سنجی یک مجموعه داده مورد بحث قرار می‌گیرد.

نتایج: بخش نتایج، یافته‌های مطالعه را با تمرکز بر عملکرد مدل یادگیری عمیق (DL) گروه ترکیبی (CNN + LSTM) ارائه می‌کند. این شامل جزئیات در مورد دقت به دست آمده، مقایسه با دیگر معماری‌هایDL ، و بینش به دست آمده از اعتبار سنجی دقیق با استفاده از مدل های تک بعدی و چند بعدی در مجموعه داده‌های تولید شده است.

نتیجه‌گیری: نتیجه گیری مفاهیم و مشارکت‌های کلیدی مطالعه را خلاصه می‌کند. این مقاله اهمیت مجموعه ترکیبی (CNN + LSTM) را در دستیابی به دقت بالای تقریباً ۹۴/۶٪ در طبقه‌بندی ترافیک غیرعادی BCI مورد بحث قرار می‌دهد. علاوه بر

این، بر اهمیت پرداختن به نگرانی های امنیتی مرتبط با BCIهای متصل به اینترنت (5G) برای کاربرد عملی آنها در زمینه IoBNTتاکید می‌کند.

کلیدواژه‌ها: اینترنت اشیاء زیست نانو، پاتوژن‌های گیاهی، یادگیری عمیق، رابط سایبری زیستی، CNN، LSTM

نوع مقاله: پژوهشی.

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