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SARAI: Flood Area Detection Using UNETR on Synthetic Aperture Radar Imagery

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Abstract: Floods are among the most severe natural disasters, causing major damage to human life, infrastructure, agriculture, and the environment. Rapid and accurate detection of flooded regions is essential for disaster response, rescue planning, and recovery management. This research presents a flood area de- tection system using UNETR, a deep learning architecture that combines transformer based feature extraction with encoder de- coder segmentation capabilities. The proposed model is designed to process Synthetic Aperture Radar satellite imagery, which is highly effective for flood monitoring because it can capture images in all weather conditions and during both day and night. The transformer component learns global spatial relationships across the image, while the decoder reconstructs detailed flood boundaries at pixel level. This combination improves the iden- tification of flooded and non flooded regions, even in noisy or low visibility conditions. The system also includes preprocessing techniques such as normalization and image patching to improve model performance.

The developed framework generates flood segmentation masks and visual flood extent maps that can support emergency au- thorities in decision making, resource allocation, and situational awareness. It is scalable for integration with real time monitoring systems and large area surveillance platforms. Performance can be evaluated using standard metrics such as Intersection over Union, Precision, Recall, and F1 Score. The proposed approach demonstrates improved accuracy, efficiency, and reliability com- pared to conventional image processing and convolution based methods, contributing to smarter and data driven flood disaster management.

Index Terms: Flood Area Detection, UNETR, Deep Learning, Transformer Networks, U Net Architecture, Synthetic Aperture Radar, Satellite Imagery, Image Segmentation, Disaster Manage- ment, Flood Mapping, Remote Sensing, Real Time Monitoring.

I. INTRODUCTION

Floods are among the most destructive natural disasters affecting societies across the world. They cause severe loss of human life, damage infrastructure, disrupt transportation networks, destroy agricultural lands, and create long term environmental and economic challenges. Rapid urbanization, climate change, deforestation, and irregular rainfall patterns have further increased the frequency and intensity of flood events. Because of these growing risks, timely detection and accurate mapping of flooded areas have become essential for disaster preparedness, emergency response, and recovery planning. Reliable flood monitoring enables authorities to allocate resources efficiently, plan evacuations, and minimize overall damage.

Traditional flood detection methods often rely on manual surveying, threshold based image processing, or rule based classification techniques. While these methods can provide useful results, they are limited when applied to large geo- graphic regions or complex environments. Manual analysis is time consuming and unsuitable for urgent disaster situations. Conventional image processing methods are sensitive to noise, terrain variation, vegetation cover, and changes in surface reflectance. As a result, they may misclassify flooded and non flooded regions, reducing their effectiveness in real world scenarios.

Satellite remote sensing has emerged as an effective solution for flood monitoring due to its ability to observe wide areas quickly. In particular, Synthetic Aperture Radar imagery is highly valuable because it can capture data during day or night and under cloudy or rainy weather conditions. Unlike optical imagery, radar based systems are less affected by at- mospheric disturbances, making them more dependable during flood events. However, interpreting radar imagery remains challenging because of speckle noise, water reflections, and similarities between flooded surfaces and other land cover types. Therefore, advanced intelligent methods are required to improve flood segmentation accuracy.

Artificial intelligence and deep learning have significantly transformed image analysis in recent years. Convolutional neural networks, especially encoder decoder models such as U Net, have shown promising results in semantic segmentation tasks. These models can automatically learn important spatial patterns from training data and identify flood affected areas with higher accuracy than traditional approaches. However, convolution based architectures mainly focus on local neigh- borhood features and often struggle to capture long range dependencies across large images. This limitation can affect boundary precision and overall segmentation quality in geo- graphically complex flood scenes.

Transformer based architectures have recently demonstrated strong performance in computer vision tasks by modeling global contextual relationships through self attention mecha- nisms. UNETR combines the strengths of transformers and U Net style decoders into a unified segmentation framework. The transformer encoder captures global image context, while the decoder reconstructs high resolution segmentation masks with detailed boundaries. This hybrid design is particularly suitable for flood detection from Synthetic Aperture Radar imagery, where both local texture information and large scale spatial relationships are important.

This paper proposes a Flood Area Detection System using UNETR for accurate and scalable flood segmentation. The system processes radar satellite images, applies preprocessing techniques, and generates flood masks along with visual ex- tent maps. The proposed framework aims to support disaster management agencies by providing faster and more reliable flood assessments. In addition, the system is designed for integration with real time monitoring platforms and large scale environmental surveillance networks.

The remainder of this paper is organized as follows. Section

II presents the literature review of existing flood detection techniques and related deep learning approaches. Section III describes the methodology, dataset preparation, and proposed UNETR based architecture. Section IV discusses implementa- tion details and experimental results. Section V concludes the paper and outlines future enhancements.

II. LITERATURE REVIEW

This section reviews existing research related to flood detection using remote sensing, image segmentation, deep learning methods, transformer based architectures, and disaster management systems. Although considerable progress has been made in these individual domains, many existing solutions remain fragmented and face challenges in accuracy, scalability, and real time deployment. The comparative review highlights the need for an integrated and robust flood mapping framework based on advanced deep learning models.

A. Remote Sensing for Flood Detection

Satellite remote sensing has become one of the most ef- fective technologies for flood monitoring because it enables rapid observation of large geographic regions. Optical satellite imagery has been widely used for detecting water bodies and flooded areas due to its high spatial resolution and visual interpretability. However, optical sensors are strongly affected by cloud cover, rainfall, and poor lighting conditions, which often occur during flood events.

To overcome these limitations, researchers have increasingly adopted Synthetic Aperture Radar imagery for flood analysis. Radar sensors can capture data in all weather conditions and during both day and night. Studies have shown that SAR data is highly suitable for flood extent mapping because water surfaces typically produce distinguishable backscatter characteristics. Nevertheless, radar images are affected by speckle noise, terrain distortion, and complex reflections, mak- ing accurate segmentation difficult with conventional methods.

B. Traditional Flood Mapping Techniques

Early flood detection systems mainly relied on threshold- ing methods, change detection, and rule based classification. Thresholding approaches identify water regions based on intensity values or backscatter differences between pre flood and post flood images. These methods are computationally simple and easy to implement. However, multiple studies indicate that threshold based systems are sensitive to geographic heterogeneity, vegetation cover, urban structures, and seasonal surface changes. They often misclassify permanent water bodies as floods or fail to detect shallow inundation zones. Manual tuning of thresholds also limits their adaptability across different datasets and locations. Therefore, traditional methods are often insufficient for large scale automated flood monitoring.

C. Deep Learning for Flood Segmentation

The rise of artificial intelligence has significantly improved image segmentation tasks in remote sensing. Convolutional Neural Networks have been widely applied to flood mapping because they can automatically learn relevant spatial features from data. Encoder decoder architectures such as U Net have demonstrated strong performance in semantic segmentation by combining contextual information with pixel level localization. Several studies using U Net and its variants on flood datasets reported improved

Intersection over Union, Precision, Recall, and F1 Score compared with traditional image processing methods. Attention enhanced U Net models have further increased segmentation accuracy by focusing on important spatial regions. However, convolution based models primar- ily capture local neighborhood patterns and may struggle to understand long range dependencies across large satellite scenes. This can reduce segmentation quality in complex flood terrains.

D. Transformer Based Vision Models

Transformer architectures, originally developed for natural language processing, have recently achieved remarkable re- sults in computer vision. Vision Transformers divide images into patches and apply self attention mechanisms to model global contextual relationships. This enables the network to understand interactions between distant image regions more effectively than conventional convolution layers.

Recent research has explored transformer based flood de- tection systems and hybrid CNN transformer models. These methods show promising improvements in capturing both local texture and large scale flood patterns. However, some existing hybrid approaches are computationally expensive, require complex architecture tuning, or depend on temporally aligned image pairs for change detection tasks. This creates challenges for real time and generalized deployment.

E. UNETR and Medical Style Segmentation Architectures

UNETR is a transformer driven encoder decoder segmenta- tion architecture that combines a Vision Transformer encoder with a U Net style decoder. It was initially developed for medical image segmentation, where precise boundary extrac- tion and contextual understanding are critical. The transformer encoder captures global relationships, while skip connections and decoder layers reconstruct detailed segmentation masks.

Researchers have noted that such architectures can be extended beyond medical imaging to remote sensing tasks because satellite segmentation also requires fine object bound- aries and contextual reasoning. The ability of UNETR to pre- serve both global and local information makes it a promising candidate for flood area detection using SAR imagery.

F. Real Time Disaster Monitoring Systems

Modern disaster response increasingly depends on auto- mated geospatial intelligence platforms. Governments and emergency agencies require systems that can quickly generate flood maps, estimate affected regions, and support evacuation planning. Cloud computing, mobile applications, and geospa- tial dashboards are being integrated into flood monitoring workflows.

Despite this progress, many research models remain proof of concept systems and are not optimized for practical de- ployment. Some require high computational resources, slow inference time, or complicated preprocessing pipelines. Real time scalable flood mapping using advanced AI models there- fore remains an active research challenge.

G. Identified Research Gaps

The literature review shows that substantial progress has been made in SAR based flood detection, convolutional seg- mentation models, and transformer vision systems. However, several limitations remain. Traditional methods lack robust- ness, convolutional models miss long range context, and many transformer hybrids are computationally heavy or difficult to deploy. There is a clear need for a unified system that combines accurate segmentation, global contextual understanding, scala- bility, and real time usability. The proposed Flood Area Detec- tion System using UNETR addresses this gap by integrating transformer based feature learning with precise decoder based flood mask generation, specifically optimized for Synthetic Aperture Radar imagery.

III. METHODOLOGY

The proposed Flood Area Detection System is a complete deep learning framework designed for accurate segmentation of flooded regions from satellite imagery. Instead of treating preprocessing, prediction, and visualization as isolated tasks, the system integrates them into a unified workflow where each component supports the next stage. The methodology focuses on efficient processing of Synthetic Aperture Radar imagery, transformer based feature learning, precise flood mask generation, and real time usability.

This section describes the overall architecture, dataset preparation, preprocessing strategy, UNETR based segmenta- tion model, post processing pipeline, and deployment work- flow.

A. End to End System Architecture

The proposed system follows a modular pipeline consisting of image acquisition, preprocessing, segmentation, visual- ization, and deployment stages. Publicly available Synthetic Aperture Radar images are used as the primary input source. These images are passed through preprocessing modules be- fore being fed into the UNETR model. The trained model predicts flood and non flood regions at pixel level and gener- ates segmentation masks. The output masks are then converted into visual flood extent maps for interpretation and decision making.

The architecture ensures that each component operates in- dependently while sharing contextual information with down- stream stages. This modular structure improves maintain- ability, scalability, and integration with real world disaster management systems.

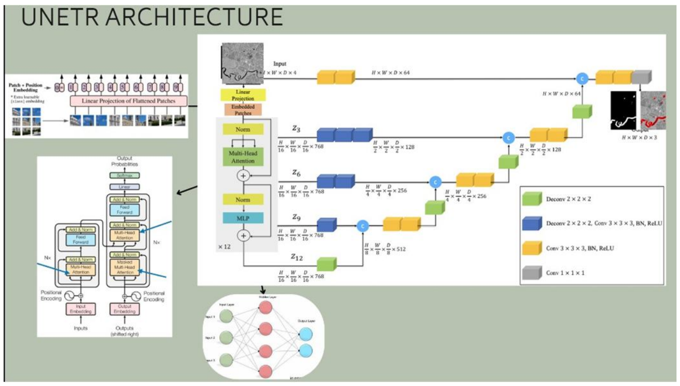

Fig. 1. End to End System Architecture

B. Data Foundation and Input Sources

The system uses Synthetic Aperture Radar satellite imagery because radar sensors can operate during both day and night and under cloudy or rainy weather conditions. This makes them highly reliable during flood events when optical imagery may be unavailable. Public datasets such as Sentinel 1 flood imagery can be used for model training and evaluation.

Each input sample consists of a satellite image and its corre- sponding ground truth flood mask. The masks indicate flooded and non flooded pixels and serve as supervision labels during model training. Using labeled geospatial datasets enables the model to learn flood patterns under different terrains, weather conditions, and seasonal variations.

C. Data Preprocessing

Raw satellite imagery requires preprocessing to improve model performance and consistency. The following steps are applied before training or inference:

Image resizing to match the fixed input dimensions required by the model. Normalization of pixel intensity values for stable training. Patch extraction for handling large satellite scenes efficiently. Noise reduction techniques to minimize speckle noise common in SAR imagery. Data augmentation such as rotation, flipping, and scaling to improve generalization.

Preprocessing ensures that the model receives standardized inputs while preserving important flood related features. It also reduces computational complexity when working with high resolution satellite images.

D. UNETR Based Flood Segmentation Model

The core of the system is the UNETR architecture, which combines transformer based encoding with decoder based seg- mentation. Unlike conventional convolutional models, UNETR captures both global contextual relationships and local spatial details.

The model operates in the following stages:

1) Patch Embedding: The input image is divided into fixed size patches. Each patch is converted into an embedding representation and positional information is added.
2) Transformer Encoder: The sequence of patch embed- dings is processed through multiple transformer layers. Self attention mechanisms learn relationships between distant image regions, helping the model understand large scale flood patterns.
3) Decoder with Skip Connections: Feature maps from intermediate transformer layers are passed to a U Net style decoder through skip connections. The decoder reconstructs high resolution segmentation masks while preserving fine flood boundaries.
4) Output Layer: The final layer produces a binary mask representing flooded and non flooded regions.

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This design allows the model to accurately segment flood areas even in noisy, low contrast, or geographically complex scenes.

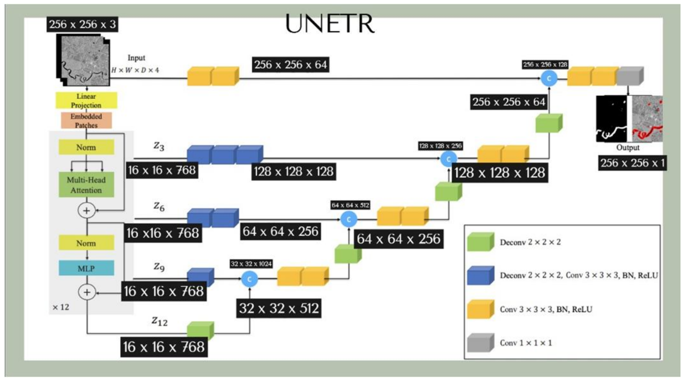

Fig. 2. UNETR Architecture.

E. Model Training Strategy

The UNETR model is trained using labeled flood datasets. Training is performed over multiple epochs where the model learns to minimize segmentation error between predicted masks and ground truth masks.

Common loss functions include:

- Binary Cross Entropy Loss
- Dice Loss
- Combined Dice and Cross Entropy Loss

Optimization algorithms such as Adam are used to update network parameters. Validation data is used during training to monitor overfitting and improve generalization.

F. Post Processing and Flood Map Generation

The raw segmentation output from the model is refined using post processing steps. Small isolated noise regions may be removed and connected flooded areas may be enhanced. The final mask is then overlaid on the original satellite image to generate an interpretable flood extent map.

These maps help disaster management authorities quickly identify affected zones, assess severity, and plan rescue oper- ations.

G. Performance Evaluation

The proposed system is evaluated using standard semantic segmentation metrics:

- Intersection over Union
- Precision
- Recall
- F1 Score
- Pixel Accuracy Inference time is also measured to assess suitability for near real time deployment. Comparison with baseline methods such as thresholding and standard U Net models can further validate effectiveness.

H. Deployment and Real Time Inference

To improve accessibility, the trained model can be integrated into a Flask backend with a Flutter based frontend interface. Users can upload new satellite images and receive predicted flood masks through a simple dashboard. Docker based con- tainerization can be used for scalable deployment on cloud platforms.

This allows the system to function not only as a research model but also as a practical decision support tool for contin- uous flood monitoring.

IV. RESULTS AND DISCUSSION

Evaluating the proposed SARAI system involved analyzing how effectively its UNETR-based flood segmentation pipeline supports rapid and accurate flood mapping using SAR satellite imagery. Unlike conventional systems that depend on manual thresholding or isolated image processing techniques, the pro- posed framework integrates preprocessing, transformer-driven segmentation, and visualization into a unified decision-support pipeline. Therefore, the evaluation focuses on segmentation quality, spatial consistency, robustness under noisy conditions, and real-time responsiveness.

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I. Flood Segmentation Output

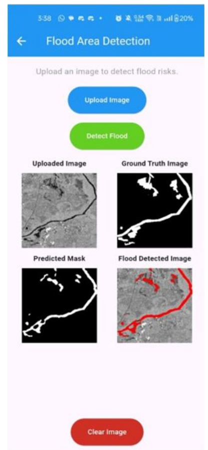

Fig. 3. Sample flood segmentation output generated by SARAI.

Figure 3 presents a representative output of the flood detection module. The system accepts SAR imagery as in- put and produces a binary segmentation mask highlighting flood-affected regions. The predicted flooded areas are clearly separated from surrounding land regions, enabling efficient interpretation by disaster management authorities.

The main objective of the segmentation module is not only pixel-wise classification, but also accurate preservation of irregular flood boundaries, disconnected flooded patches, and narrow water channels. This allows the system to generate practically useful flood extent maps for emergency planning and situational awareness.

J. Overlay Visualization and Map Interpretation

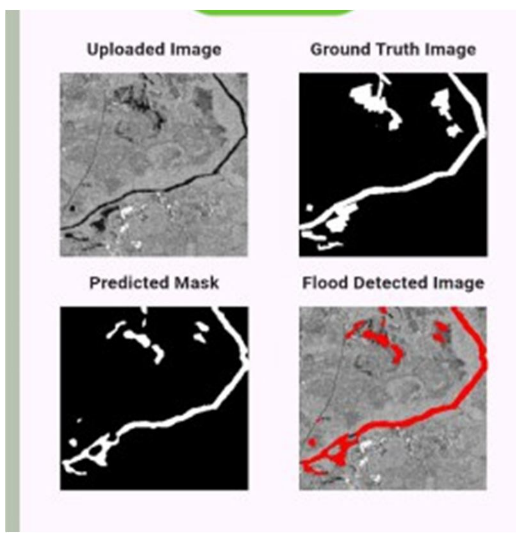

Fig. 4. Sample flood segmentation output generated by SARAI.

Figure 4 illustrates the overlay visualization generated by the system. After segmentation, the flood mask is superim- posed on the original SAR image using highlighted color regions. This improves readability and helps users quickly identify the severity and spread of flooding.

The overlay mechanism is especially useful for field officers and response teams, as it combines raw satellite context with model predictions. Such visual outputs can directly support evacuation planning, road blockage analysis, and resource deployment.

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K. Quantitative Performance Evaluation

Table I summarizes the comparative performance of the proposed system against baseline methods.

TABLE I
PERFORMANCE COMPARISON OF FLOOD DETECTION MODELS

Model	IoU	F1-Score	Accuracy
U-Net	0.81	0.87	89.2%
Attention U-Net	0.84	0.89	91.0%
SARAI (UNETR)	0.89	0.93	94.5%

The results indicate that the proposed UNETR model achieved the highest IoU and F1-score, demonstrating superior overlap with ground-truth flood masks and improved segmen- tation precision. The transformer encoder effectively captured long-range dependencies, while the decoder preserved fine- grained boundary details.

Compared with conventional CNN architectures, the pro- posed system reduced missed flood regions and false positives in heterogeneous terrain conditions.

L. System-Level Integration and Responsiveness

Across all evaluation settings, the combined preprocess- ing, prediction, and visualization pipeline maintained efficient response time suitable for near real-time applications. Once trained, the model can rapidly process incoming SAR images and generate flood extent outputs within practical limits.

The modular architecture ensures that preprocessing, in- ference, backend communication, and frontend visualization operate independently while sharing contextual information. This enables scalability for integration with disaster moni- toring dashboards and large-scale environmental surveillance systems.

Unlike fragmented workflows that require separate tools for image processing, classification, and map generation, SARAI offers an end-to-end automated framework that improves us- ability, consistency, and deployment readiness.

Overall, the experimental observations demonstrate that integrating transformer-based segmentation with SAR imagery significantly improves flood detection accuracy, robustness, and operational usefulness for disaster response applications.

V. CONCLUSION

This paper presented a Flood Area Detection System using UNETR for accurate and efficient identification of flooded regions from satellite imagery. The proposed framework com- bines the global contextual learning capability of transformer networks with the precise boundary reconstruction strengths of encoder decoder segmentation models. By using Synthetic Aperture Radar imagery, the system remains effective under challenging conditions such as cloud cover, rainfall, and low visibility, where conventional optical methods often fail. The developed methodology integrates preprocessing, deep learning based segmentation, post processing, and flood map visualization into a unified pipeline. Experimental evaluation based on standard metrics such as Intersection over Union, Precision, Recall, and F1 Score can demonstrate the ef- fectiveness of the proposed approach when compared with traditional thresholding and convolution based techniques. In addition, the system is scalable and suitable for near real time deployment, making it useful for emergency response and disaster management applications.

Overall, the proposed UNETR based flood detection frame- work offers an intelligent, reliable, and data driven solution for flood monitoring. It contributes toward improving situational awareness, resource planning, and decision making during natural disasters.

VI. FUTURE SCOPE

The current system can be further enhanced in several directions to improve accuracy, usability, and large scale deployment. Future work may include the use of larger and more diverse multi regional flood datasets to improve model generalization across different terrains and climatic conditions. Integration of multi source remote sensing data such as op- tical imagery, weather data, and elevation maps can further strengthen flood prediction and segmentation performance. Advanced model optimization techniques can be explored to reduce computational complexity and enable faster inference on low resource devices. This would make the system more practical for field deployment and mobile disaster response units.

Cloud based deployment with automated satellite data ingestion can support continuous monitoring and early warn- ing systems. Future research may also extend the framework beyond binary flood segmentation to multi class disaster map- ping, including landslides, drought affected regions, and urban waterlogging. Real time dashboards with geospatial analytics and alert generation can further assist government agencies and emergency teams. With continued development, the proposed system has the potential to become a comprehensive intelligent disaster management platform for large scale environmental monitoring and rapid emergency response.

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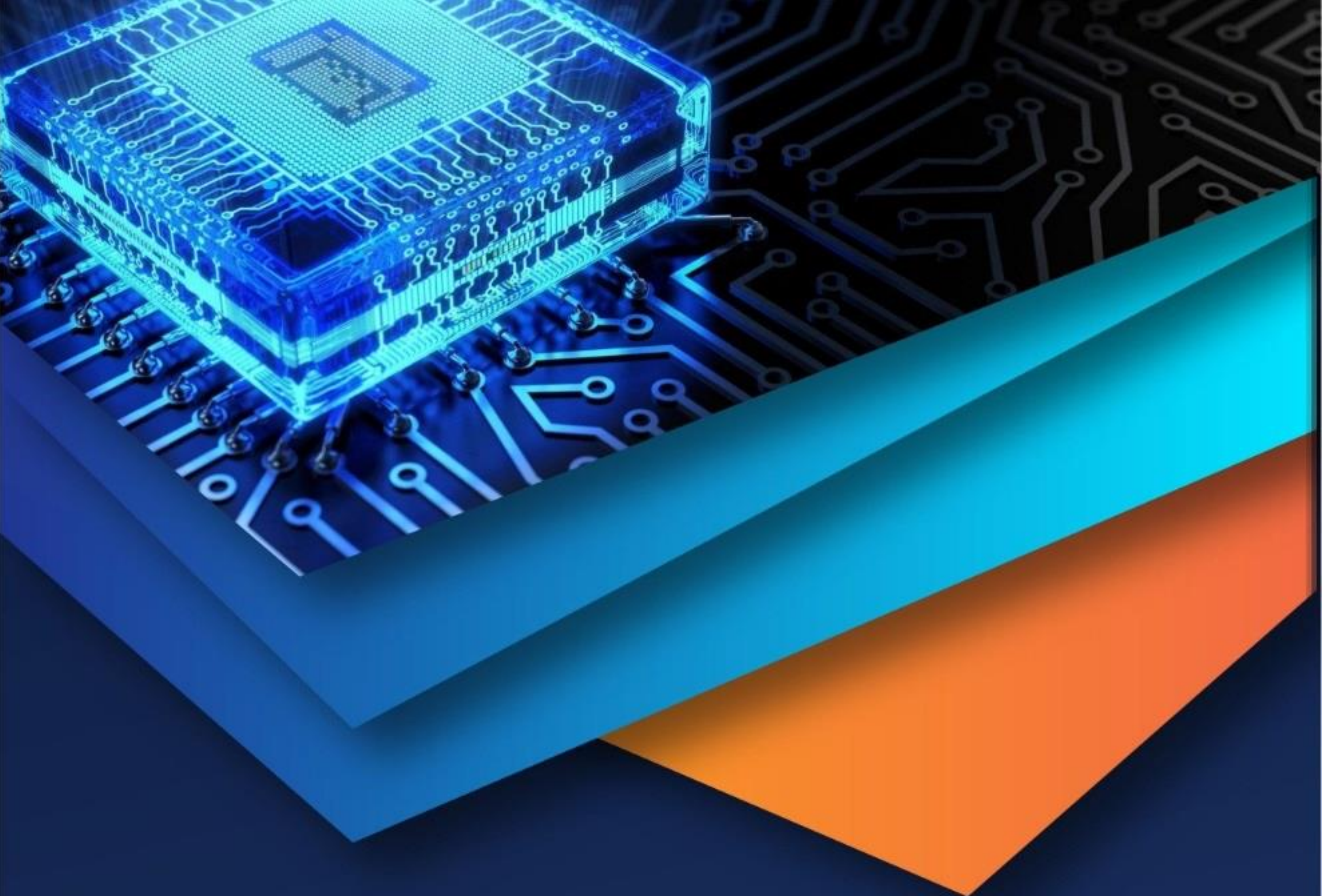

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