Detecting Oil Spills At Marine Environment Using Automatic Identification System (AIS) And Satellite Datasets

Tushar Pandey
JSS Academy Of Technical Education, Noida, Uttar Pradesh, India

Vaani Pathariya
JSS Academy Of Technical Education, Noida, Uttar Pradesh, India

Vaibhav Anand
JSS Academy Of Technical Education, Noida, Uttar Pradesh, India

***Abstract*—The detection of oil spills in marine environments prevents and speeds up response efforts, avoiding environmental damage. Here, we proposed a state-of-the-art robust method to detect oil spills. A huge dataset with images and frames, extracted from the video data downloaded from Google, augmented the dataset after the extraction of frames. Each image is also carefully labeled in order to get good training data. We trained our oil spill detection model with the use of the Yolov8 segmentation model in order to accurately identify and segment the oil spills in ocean environments. K-means and Truncated Linear Stretching algorithms are combined with the trained model weights in order to increase the accuracy of model detection. The model is doing exceptionally well; hence it has high detection accuracy with excellent segmentation capabilities. Our results indicate that this method is very efficient for real-time oil spill detection and, therefore, is promising for environmental monitoring and disaster management. For the training metrics, the model had more than 97% accuracy after 100 epochs. During the evaluation process, the best detection rates were achieved at 94% accuracy for F1, 93.9% accuracy for precision, and 95.5% mAP@0.5 accuracy for recall curves.**

I. KEYWORDS

Marine safety, oil spill detection, image segmentation, object-detection

II. INTRODUCTION

Oil spills, or liquid petroleum hydrocarbon discharge, can occur at any stage of the life cycle of oil, including exploration, production, transportation, refining, storage, and distribution. They are mainly caused by external factors with highly destructive impacts on water systems, ice-covered areas, and land. Oil spills in marine ecosystems expose the related biodiversity, fisheries, and socio-economic interests to potential harms; hence the detection ought to be done timely enough to reduce damages on the environment and ecological degradation. Yet oil spills continue striking worldwide. Statistically and according to statistics from the year 2023 alone, one massive spill is recorded above 700 tons while nine mediums spill happened within 7-700 tons. The biggest spill was heavy fuel oil in Asia in February. Including other low-sulfur fuel oil, crude oil, and gasoline spills, the estimated loss was 2000 tons. This calls for the necessity of advanced oil spill detection and monitoring systems to be able to respond and mitigate better. This means that its behavior in water will depend on its properties like surface tension and viscosity as well as environmental conditions, for example, wind. It spreads on the surface when spilled and forms oil slicks. The following processes of degradation, though make detection and monitoring challenging. Methods for oil spill detection include satellite imagery, aerial surveillance, and manual reporting.

Satellite remote sensing provides very real-time large-scale observations. SAR is popular technology to detect oil slick due to the fact that it detects without consideration of weather conditions and illumination. It measures backscattering coefficient to determine clean water from oil-polluted one. Generally, SAR-based techniques had suffered from false alarms due to similar backscatters that exist in algae bloom and shallow water scenarios. For the second time, again interference from the presence of winds has affected the operation of SAR also. This breakthrough came about in PolSARs since concepts for employment of several polarizations for preparation of the necessary details involving target surfaces emerged into realities. This multi-polarization approach enhances the characterization of surface materials. PolSAR is, therefore, an effective tool in environmental monitoring.

Despite its effectiveness, PolSAR requires complex algorithms to interpret complex data. The traditional feature extraction methods are time-consuming and domain-dependent. Deep learning has emerged as a transformative technology for the detection of oil spills over many of the challenges found with traditional methods. Deep learning models surpass traditional machine learning by abstracting out high-level features from raw data. In the application of oil spill classification from SAR images, AlexNet was used by Deng et al. Yang et al. applied YOLOv4 to detect spills under severe conditions such as shadows and low-lighting conditions. However, in anchor-based approaches, the major drawback of this is that oil spills may be of any type of shape or size. Therefore, its detection results in suboptimal behavior.

Overcoming these hardships, this work built a customized dataset of high-resolution images corresponding to oil spill with techniques of semantic segmentation annotated thereon.

This dataset gave accurate localizations of oil spill areas. Further, it facilitated refining the YOLOv8 model. Some of the techniques used during this process - K-means clustering and Truncated Linear Stretching helped bring out accuracy as well as robustness in detection. This research contributes to oil spill detection in marine environments as follows: 1. Creating a high-quality, customized dataset from different sources. 2. Designing a YOLOv8-based model for the segmentation of oil spills. 3. Enhancing the accuracy of detection by using advanced image processing techniques.

This paper is divided into two parts. Section 2 will be on related work, which consists of advanced research and the limitations of various techniques in oil spill detection, while Section 3 would present the method of dataset preparation along with semantic segmentation and training of YOLOv8.

Section 4 discusses the experimental results of the proposed approach through examples and the obtained quantitative performance metrics. Section 5 Conclusion The section summarises key findings and future work directions. The approach proposed here for oil spill detection is the integration of deep learning with a well-structured dataset and brings in a novel method of monitoring marine environments in real time and in an efficient manner.

III. Literature Review

Hussain A. , Hussain T. , Ullah I. , Muminov B. , Khan M.Z. , Alfarraj O. , Gafar A. [2023] : This nomenclature has coined a name, CR-NBEER that represents a cooperative relay neighboring based energy-efficient routing protocol especially suited to Marine Underwater Sensor Networks. Applying cooperative relays in amalgamation with the best forwarders that have been shown to be neighbors, has introduced very meaningful improvement in the context of energy efficiency besides reliable communication, particularly with the scope of the research conducted. The energy consumption level is pretty high in the water and unreliable communication links are pretty challenging in this underwater environment. The outcomes in terms of network performance in addition to energy efficiency exhibited in the simulation have rendered noteworthy improvements as compared with currently available routing protocols in use.

Umirzakova S. , Mardieva S. , Muksimova S. , Ahmad S. , Whangbo T. [2023] : This work presents a novel method that improves the super-resolution of medical images with the aid of a deep residual feature distillation channel attention network or DRFDCAN. It was enhanced both in terms of resolution as well as quality using highly efficient mechanisms for feature extraction coupled with channel attention mechanisms. Hence, this methodology stood to be the best and most efficient that existed for all applications in the domain of medical imaging. This embodies the capability of DRFDCAN to enable physicians with an accurate diagnosis and interpretation correctly by image reconstruction.

Makhmudov F. , Kultimuratov A. , Cho Y.-I. [2024] : This scholarly article deals with intricate features in the implementation of an attention mechanism, which, ironically, is crucial in pre-existing BERT and CNN architectures. The major takeaway from this research was huge improvement and optimization regarding the process of multimodal emotion recognition as it is very related in understanding human emotions in its diverse forms through recognizing data. The purpose of research is to better or improvise the way of processing textual data and visual data effectively so that this would eventually lead to an outcome derived from a higher accuracy and precision in subsequent analysis of emotions. Additionally, the used method of employed demonstrates a level of performance that is significantly higher as compared with conventional benchmark approaches that are generally practiced in the field. Outcomes that have resulted from this research go to represent and show the tremendous opportunity that is provided by the attention-driven architectures, specially in the context of these complex and intricate tasks pertaining to emotion recognition.

Abdusalomov A.B. , Mukhiddinov M. , Whangbo T.K. [2023] : This research paper uses a method of highly advanced deep learning, which is explicitly constructed to detect brain tumors from magnetic resonance imaging scans. Furthermore, this paper demonstrates the benefits offered by the use of an advanced neural network in an effort to dramatically improve on the efficiency of tumor detection and classification processes. Basically, it has marked much more significant milestones compared with the traditional diagnosis methods conventionally applied in the given sector. The basis of the work provides the most conclusive evidence for enhancing medical image analysis through the application of AI techniques to help analyze a brain tumor more comprehensively.

Juneja S. , Nauman A. , Uppal M. [2024] : This paper introduces a new approach involving the use of a defect prediction model based on machine learning, specifically developed using the MLP algorithm, to aim for the significant improvement of the software systems' overall reliability. A crucial objective of this model is to predict defects beforehand in an early stage such that developers can take this as an opportunity to address and solve those problems before they become larger and more difficult. More than that, the study vividly shows how the use of the MLP algorithm plays an important role in the process of improving the quality of the software by systematically locating the defects through the analysis of historical data. The output results of this research further underscore the vast potential offered by machine learning in terms of software maintenance, especially toward achieving better performance and vastly diminishing the risks of failures involved.

Umirzakova S. , Ahmad S. , Khan L.U. , Whangbo T. [2023] : The authors take a comprehensive review of medical image super-resolution techniques and applications into smart health care, especially within methods that enhance the images gained at lower resolutions as commonly used in the detection or diagnosis and treatment procedure. The approach of the deep survey is based on both CNN and GAN. Within the article, the authors introduce a discussion on challenges and weaknesses for noise reduction and removal. It discusses the role of SR in emerging smart health-care systems that integrate AI and IoT technologies to better care for patients. Included in the list of promising areas for further research are real-time enhancement and multi-modal SR, amongst others. The bottom line is that such a survey does indicate very real potential for SR in fundamentally improving medical imaging, hence improving healthcare delivery.

Norkobil Saydirasulovich S. , Abdusalomov A. , Jamil M.K. , Nasimov R. , Kozhamzharova D. , Cho Y.-I. [2023] : It provides a sophisticated method of fire detection regarding the YOLOv6 algorithm meant for smart city applications. The methodology works based on a YOLOv6 model of object detection, being one of the state-of-the-art models that could improve precision and efficiency on real-time fire detection. The primary challenges in relation to the study are high-speed identification of fire incidences during the presence of various environmental conditions. The model is tested using precision, recall, and overall performance in detecting fires from video feeds captured by smart city cameras. For the system, there are some significant improvements seen in detection rates as compared to traditional methods.

Muksimova S. , Umirzakova S. , Mardieva S. , Cho Y.-I. [2023] : This paper presents new model-based approaches in enhancing the performance of medical image denoising for precision diagnosis. The authors introduce a new framework whereby a teacher model guides the learning of the student model to pick up strong features that improve the denoising and hold significant details in the medical images. It shows that high-quality imaging is essential for proper determination and treatment. It assesses the potential models of noise removal in the process of maintaining clarity of crucial features of images. It is used on various modalities of medical imaging and has been proven to have better denoising performances than conventional techniques. Quality improvement through the teacher-student approach has resulted in better diagnostics. According to this paper, this technique possibly might develop applications in medicine to use medical imaging precision for great health.

Abdusalomov A.B. , Islam B.M.S. , Nasimov R. , Mukhiddinov M. , Whangbo T.K. [2023]: This paper proposes a new technique for the improvement of forest fire detection by integrating deep learning methods with the Detectron2 model. According to this, the authors have forwarded the application of Detectron2, as it represents the state-of-the-art object detection framework that facilitates the improved accuracy and efficiency in forest fire detection. This method utilizes deep learning in processing images associated with real-time feature-related fire detection, even at challenging conditions like smoke and varying lighting. Comparing this with the traditional methods, there was significant improvement in fire detection. The model was tried on different datasets, giving strong results in terms of precision and recall. This paper reveals possibilities in applying high-performance AI models to monitoring the environment and in detecting early stages of fire outbreak. The application of this approach will be in use in practice in order to contribute to the timely response and the strategies about forest management.

TABLE I
GAP ANALYSIS

S.N	Author	Proposed System	Gap
1	Hussain A. , Hussain T. , Ullah I. , Muminov B. , Khan M.Z. , Alfarraj O. , Gafar A	This nomenclature has coined a name, CR-NBEER that represents a cooperative relay neighboring based energy-efficient routing protocol especially suited to Marine Underwater Sensor Networks. Applying cooperative relays in amalgamation with the best forwarders that have been shown to be neighbors, has introduced very meaningful improvement in the context of energy efficiency besides reliable communication, particularly with the scope of the research conducted.	• Scalability in Large Networks: It does not describe how the CR-NBEER protocol would be in an underwater sensor network of very large scale. • Adaptation to Dynamically Changing Marine Environments: Underwater sensor networks in a marine environment are much more dynamic in the nature of water currents, salinity, and temperature. So, at this point of time, there is not much insight into how the CR-NBEER system is going to behave in such environments.
2	Umirzakova S. , Mardieva S. , Muksimova S. , Ahmad S. , Whangbo T	This work presents a novel method that improves the super-resolution of medical images with the aid of a deep residual feature distillation channel attention network or DRFDCAN. It was enhanced both in terms of resolution as well as quality using highly efficient mechanisms for feature extraction coupled with channel attention mechanisms.	• Fewer Modalities of Medical Images: The paper reduces the types of the possible medical images, which can be explored as MRI and CT scans but does not test its proposed network with much more extensive ranges of the imaging modalities, such as ultrasound or PET scans. • Generalization to data variations of the patients: These deep learning models are quite unlikely to be trained on different sets of data with age variability and ethnicity variabilities and also variability about the nature of medical condition. That may impact generalization ability as well as robustness of the solution.
3	Makhmudov F. , Kultimuratov A. , Cho Y.-I	This scholarly article deals with intricate features in the implementation of an attention mechanism, which, ironically, is crucial in pre-existing BERT and CNN architectures. The major takeaway from this research was huge improvement and optimization regarding the process of multimodal emotion recognition as it is very related in understanding human emotions in its diverse forms through recognizing data.	• Limited multimodal data sources are considered as one likely focus area during a study as it only studies some modes, like the text and images, at the exclusion of other like audio and physiological signals highly valued to fully identify all emotions. • Scalability to Real-World Scenarios: The proposed approach might not account for noisy or incomplete data, which is quite common in the practical applications of multimodal emotion recognition.
4	Abdusalomov A.B. , Mukhiddinov M. , Whangbo T.K.	This research paper uses a method of highly advanced deep learning, which is explicitly constructed to detect brain tumors from magnetic resonance imaging scans. Furthermore, this paper demonstrates the benefits offered by the use of an advanced neural network in an effort to dramatically improve on the efficiency of tumor detection and classification processes.	• Scalability to Real-World Scenarios: The proposed model may not address the real-world challenges that are noisy or incomplete data in real applications of multimodal emotion recognition. • Cross-Cultural Emotion Variability: The paper could potentially omit discussing how cultural variations in emotional expression and interpretation could affect the performance of the emotion recognition system.
5	Juneja S. , Nauman A. , Uppal M.	This paper introduces a new approach involving the use of a defect prediction model based on machine learning, specifically developed using the MLP algorithm, to aim for the significant improvement of the software systems' overall reliability. A crucial objective of this model is to predict defects beforehand in an early stage such that developers can take this as an opportunity to address and solve those problems before they become larger and more difficult.	• Software systems are not validated: the proposed model may only validate in terms of benchmark datasets whereas in the real world, usual software systems have peculiar complexities and differences that may influence the performance of the model. • It does not focus on the interpretability or explainability of MLP-based predictions, which is really important for developers to understand why the predicted defects are generated and have confidence in the model for practical usage.
6	Umirzakova S. , Ahmad S. , Khan L.U. , Whangbo T.	The authors take a comprehensive review of medical image super-resolution techniques and applications into smart health care, especially within methods that enhance the images gained at lower resolutions as commonly used in the detection or diagnosis and treatment procedure. The approach of the deep survey is based on both CNN and GAN.	• Real-Time Medical Image Enhancement Challenges and solutions for real-time medical image super-resolution SR are critical, which is important in various time-sensitive medical applications including emergency care or intraoperative imaging. • Generalization across diverse patient demographics: There could be no discussion about the performance of SR methods for diverse patient demographics such as age, gender, ethnicity, or medical conditions affecting image characteristics and outcomes in diagnosis.
7	Norkobil Saydirasulovich S. , Abdusalomov A. , Jamil M.K. , Nasimov R. , Kozhamzharova D. , Cho Y.-I.	It provides a sophisticated method of fire detection regarding the YOLOv6 algorithm meant for smart city applications. The methodology works based on a YOLOv6 model of object detection, being one of the state-of-the-art models that could improve precision and efficiency on real-time fire detection.	• Real-Time Processing and Latency Capability: The paper does not adequately analyze whether the system might be able to capture video data in low-latency real-time, which is required for timely fire detection with rapid emergency response in high-dynamic large cities. • The model based on fire detection, though it may not portray how the system of fire detection would work with other intelligent city infrastructures; however, maybe it is being integrated to a traffic management system, to the public safety network or the automated response emergency systems.
8	Muksimova S. , Umirzakova S. , Mardieva S. , Cho Y.-I.	This paper presents new model-based approaches in enhancing the performance of medical image denoising for precision diagnosis. The authors introduce a new framework whereby a teacher model guides the learning of the student model to pick up strong features that improve the denoising and hold significant details in the medical images.	• Interpretable and transparent: the teacher-student model has to interpret the outcome of the decisions made by it in the denoising information in the clinician level and their confidence and reasoning with it must be important for reason.
9	Abdusalomov A.B. , Islam B.M.S. , Nasimov R. , Mukhiddinov M. , Whangbo T.K.	This paper proposes a new technique for the improvement of forest fire detection by integrating deep learning methods with the Detectron2 model. According to this, the authors have forwarded the application of Detectron2, as it represents the state-of-the-art object detection framework that facilitates the improved accuracy and efficiency in forest fire detection. This method utilizes deep learning in processing images associated with real-time feature-related fire detection, even at challenging conditions like smoke and varying lighting. Comparing this with the traditional methods, there was significant improvement in fire detection. The model was tried on different datasets, giving strong results in terms of precision and recall.	• Limited Testing for Varying Environmental Conditions: The developed model can only be tested by the authors in specific forest environments or conditions. In contrast, the actual, real environmental conditions such as changeable weather, types of terrain, and different types of forest ecosystems are sure to affect the accuracy in fire detection.

IV. Proposed Work

Oil Spill Detection in Marine Environment Based on the Use of Data from the AIS and the Satellite Image with YOLO.

This intelligent system is towards the detection of oil spills in marine environments using AIS and satellite data. Cutting-edge computer vision techniques used in this smart system apply YOLO (You Only Look Once) toward efficient oil spill detection. This integration of AIS data will increase the accuracy of detection further to identify oil spill incidents promptly. This is essential in responding and mitigating the event. This system will be useful to environmental organizations, marine researchers, and emergency response teams for providing timely insights into improving disaster management strategies.

Key Features of the Proposed System-

1. Automated Data Retrieval- Collect data from AIS to gain real-time insights into the vessel's locations and activities around possible oil spill areas Obtain satellite images through Copernicus Sentinel-1 or Landsat sources that provide an overview of huge ocean areas for oil spills

2. Preprocessing of Satellite and AIS Data- Pre-processing of AIS data which cleans and formats to get it readable for the analysis, synchronized timestamp with satellite image. Process images with methods like image enhancements, noise removal, contrast adjustment to enhance the outlook of oil spills.

3. Oil Spill Detection by YOLO- Using deep learning object detection models like YOLO over satellite images to identify signatures of oil spills. Custom train YOLO models on oil spill datasets for anomaly classification into oil spills. Predictions are going to be in real time.

4. AIS Data Integration- Integrate AIS ship data with the satellite image to correlate the activity of the ship with the occurrence of the oil spill. This is cross-checked with the AIS data where a vessel that may have caused the spill is indicated, thereby enhancing the detection model's accuracy.

System Objectives-

1. Real-Time Oil Spill Detection- Real-time identification of oil spills using satellite imagery and AIS data to respond to disasters in a timely manner.

2. Environmental Impact Assessment- To help environmental experts and researchers estimate the volumes of oil spills and effects on marine life and other ecosystems.

3. Improved Observations- Continuous scanning of marine environments with early warnings about oil spills and possibly maritime accidents.

Expected Outputs-

1. Better Spill Detection Using Oil Spill- The incorporation of AIS and satellite data helps in the better detection of spills, thereby leading to a better understanding of the spill patterns and sources.

2. Faster Response and Mitigation- Quick identification and reporting of events of oil spill allow prompt response actions, hence containment and limit environmental damage.

3. Data-Driven Insights- Actionable insights toward stakeholders through deep analysis of all data enhance policies and responses for better management of an oil spill.

Sequential Process of the System-

1. Data Collection (AIS Satellite Imagery Retrieval)- Use sources like Copernicus Sentinel-1 or Landsat for accessing satellite imagery over vast oceanic areas. Gather AIS data that tracks vessels' location and movement over potential oil spill sites.

2. Preprocessing Data- Clean and preprocess the AIS data by removing noise, rectifying timestamps, and normalize it to align with satellite image timestamps. Preprocess the satellite images to enhance the image quality and regions where detection of an oil spill might be feasible.

3. Oil Spill Detection using YOLO- Apply the deep learning model YOLO over the satellite images for possible oil spills. Apply the custom-trained YOLO model over the oil spill datasets for detection and classification of oil spills as objects.

4. Integration and Reporting- Correlate the data obtained from AIS with the data obtained from the satellite imagery for validation of the spill event. Visualize the results on an interactive dashboard and allow the generation of detailed reports such as CSV files for further analysis.

Libraries and Algorithms Applied-

1. YOLO for Object Detection- The primary deep learning model applied for real-time object detection is YOLO. This is applied to the oil spill detection and classification from the satellite images.

2. Flask for Developing the Web Interface- Flask will be applied to develop an interactive web interface where the user can input queries or upload data for oil spill detection analysis.

3. Handling of AIS Data (Pandas)- Continued use of pandas in processing and analytics for integration of vessel movement data into seamless satellite images.

4. OpenCV for Processing the Satellite Images- Processing of the satellite images using OpenCV to improve the quality of these images while extracting the pertinent features prior to analysis.

5. Training of the YOLO using TensorFlow/Keras- This project uses TensorFlow/Keras in the training of YOLO models in terms of oil spill case detection based on the instances captured within labeled datasets and sat imageries.

6. Geospatial Mapping (Folium or Leaflet)- Geospatial libraries such as Folium are used in plotting the locations of the detected oil spills on interactive maps that help users track and assess spills in real-time.

Data Flow-

1. User Input- Input coordinates of interest, upload satellite images, or input an AIS query through the web interface.

2. Data Collection- Download satellite images from open sources such as Sentinel-1 and retrieve AIS data from the respective databases or APIs.

3. Preprocessing- Clean up and process the AIS data and satellite images to be usable in analysis.

4. Oil Spill Detection- It uses a model of YOLO for classifying spills after oil spill detection through application of satellite images. Its validation of vessel activities that are close to spills after they have been detected by means of AIS data.

5. Visualisation and Reporting- All oil spill detections marked on a map are accompanied with reporting intended to raise an alarm to appropriate users or stakeholders of identified spill events.

V. Conclusion

This paper formulates the problem of detecting marine oil spills as an important approach toward environmental damage prevention. We have proposed a sophisticated framework using novel techniques of image enhancement that incorporate state-of-the-art deep learning approaches. We prepared a very large dataset of images and video frames properly labeled so that robust models could be trained. We are using the YOLO-v8 segmentation model as its performance in detecting and segmenting oil spills in complex marine environments is known. The integration of K-means clustering and TLS in the optimization of the model. K-means groups pixels by color, hence underlining oil spill color patterns that enhance segmentation. TLS increased contrast to such an extent that it makes the oil spill feature more evident, improving on the learning process of the model. This approach can achieve high detection accuracy while being precise in segmentation. This integrated approach is effectively utilized in environmental monitoring and disaster management. Future work includes improving data set size and spill classes thickness-based in the introduction of spill detection, with accurate assessment of this.

VI. Future Scope

The integration of Automatic Identification System (AIS) and satellite datasets for detecting oil spills in marine environments presents vast opportunities for advancement. Future systems will focus on enhancing data fusion capabilities by integrating multisource information, including higher-resolution satellite imagery, real-time AIS feeds, meteorological data, and Internet of Things (IoT) sensors. This approach will enable more comprehensive monitoring and analysis of spill incidents.

Real-time monitoring and predictive systems represent a critical area of development. Advanced algorithms leveraging artificial intelligence (AI) can facilitate instant detection, spill trajectory prediction, and timely identification of responsible vessels. Enhancements in deep learning models, such as improved segmentation techniques and explainable AI frameworks, will refine detection accuracy while building trust in automated systems.

Expanding high-quality datasets will also be essential for training robust models to handle diverse spill scenarios, accounting for variations in oil types, environmental conditions, and geographic regions. Additionally, developments in spill source attribution techniques will help pinpoint pollution sources more accurately, ensuring better accountability and compliance with maritime laws.

In the long term, these advancements will revolutionize environmental monitoring, enabling proactive measures to mitigate the ecological and socio-economic impacts of oil spills, thereby fostering a cleaner, safer marine environment.

References

[1] Hussain A. , Hussain T. , Ullah I. , Muminov B. , Khan M.Z. , Alfarraj O. , Gafar A. CR-NBEER: Cooperative-Relay Neighboring-Based Energy Efficient Routing Protocol for Marine Underwater Sensor Networks. J. Mar. Sci. Eng. 2023, 11, 1474. [Google Scholar] [CrossRef]

[2] Umirzakova S. , Mardieva S. , Muksimova S. , Ahmad S. , Whangbo T. Enhancing the Super-Resolution of Medical Images: Introducing the Deep Residual Feature Distillation Channel Attention Network for Optimized Performance and Efficiency. Bioengineering 2023, 10, 1332. [Google Scholar] [CrossRef]

[3] Makhmudov F. , Kultimuratov A. , Cho Y.-I. Enhancing Multimodal Emotion Recognition through Attention Mechanisms in BERT and CNN Architectures. Appl. Sci. 2024, 14, 4199. [Google Scholar] [CrossRef]

[4] Abdusalomov A.B. , Mukhiddinov M. , Whangbo T.K. Brain tumor detection based on deep learning approaches and magnetic resonance imaging. Cancers 2023, 15, 4172. [Google Scholar] [CrossRef]

[5] Juneja S. , Nauman A. , Uppal M. Machine learning-based defect prediction model using multilayer perceptron algorithm for escalating the reliability of the software. J. Supercomput. 2024, 80, 10122–10147. [Google Scholar] [CrossRef]

[6] Umirzakova S. , Ahmad S. , Khan L.U. , Whangbo T. Medical image super-resolution for smart healthcare applications: A comprehensive survey. Inf. Fuion 2023, 103, 102075. [Google Scholar]

[7] Norkobil Saydirasulovich S. , Abdusalomov A. , Jamil M.K. , Nasimov R. , Kozhamzharova D. , Cho Y.-I. A YOLOv6-Based Improved Fire Detection Approach for Smart City Environments. Sensors 2023, 23, 3161. [Google Scholar] [CrossRef]

[8] Muksimova S. , Umirzakova S. , Mardieva S. , Cho Y.-I. Enhancing Medical Image Denoising with Innovative Teacher–Student Model-Based Approaches for Precision Diagnostics. Sensors 2023, 23, 9502. [Google Scholar] [CrossRef]

[9] Abdusalomov A.B. , Islam B.M.S. , Nasimov R. , Mukhiddinov M. , Whangbo T.K. An Improved Forest Fire Detection Method Based on the Detectron2 Model and a Deep Learning Approach. Sensors 2023, 23, 1512. [Google Scholar] [CrossRef]

[10] Farkhod A. , Abdusalomov A.B. , Mukhiddinov M. , Cho Y.-I. Development of Real-Time Landmark-Based Emotion Recognition CNN for Masked Faces. Sensors 2022, 22, 8704. [Google Scholar] [CrossRef]