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AUTOMATIC INDEXATION OF CULTURAL HERITAGE 3D OBJECT

Abstract *There has been significant evolution in the fields of 3D digitization thanks to the development of 3D reconstruction and geometry processing. The results of digitization researches have been widely applied in many fields, especially in Cultural Heritage and Archaeology. Reconstruction, characterization and annotation of components forming 3D objects have become an effective tool for research, conservation and promotion of archaeological relics. The aim of this paper is to propose a process of 3D model reconstruction, segmentation and annotation on the basis of a enhanced corresponding 2D dataset. A machine learning method is used for the semantic segmentation of 2D images, thereby label, annotate and reconstruct a 3D model based upon links between distinctive invariant features, orientation of images, and depth map of images. The initial result as a data basis for research, reconstruction and identification of parts in 3D objects is applied in the reconstruction of archaeological relics, object identification, 3D printing, etc. Our work uses the data collected from the Museum of Cham Sculpture DaNang and the Myson QuangNam sanctuary in VietNam, to carry out the proposed method.*

Keywords 3D reconstruction, cultural heritage, semantic annotation, 3D digitization

Citation Computer Science 26(1) 2025: 5–25

1. Introduction

In Vietnam and neighboring countries, the Champa cultural heritage domain is very important. There are a variety of models of (tangible) cultural heritages and archaeological objects [6]. Management and preservation of the Champa archaeological remains are of particular significance in terms of their religion and origin. However, over time these remains have become extinct, and they are in needs of urgent protection. Cultural heritage items are priceless and of very high historical values. Maintaining and conserving these assets is a top priority for all nations around the world [2]. The purpose of preserving digital cultural heritage is not limited to the persistence of historical archives, as it can provide a good reference for creating applications on cultural heritage data with the purpose of information sharing and cultural communication.

Initially, 3D digital mockups of cultural heritage items were used for conservation and archives. As 3D digitization becomes cheaper and more affordable, processing 3D data (measuring, comparing, indexing...) has started a trend in archaeological studies. On the other hand, the development of reconstruction and analysis of 3D model researches has grown rapidly for applications such as computer vision, virtual reality, digital heritage and many others [3, 14].

The 3D model enables us to have different views, from overview to details, and to analyze objects according to many different criteria. There are many methods and tools for reconstruction of models and samples in various ways such as using scanners, magnetic resonance imaging, and reconstruction from 2D images. The outcomes are used to segment, re-identify, and rebuild objects. Models and artifact samples must be kept and conserved digitally in light of recent natural disasters, climate change, and looming devastation, therefore it is enabling the capture and digitization of 3D models of historical and archaeological artefacts.

We propose the method of data collection for 3D model reconstruction from 2D images and create a set of model training data for segmentation, analysis and annotation of parts of 2D objects. Our method is based upon the simultaneous combination of recognition, segmentation, and annotation on 2D images and conversion of these segmentations and annotation to 3D images of the same object. Then, we will carry out the annotation and segmentation of 3D objects based upon the analysis of features and links between them. The experimentation data is a set of Cham statues from Champa culture in the central region of Vietnam (DaNang, MySon). These statues are similar in material, color, and shapes.

This paper has the following layout and structure: Section 1: Introduction, Section 2: Introduction to some researches related to 3D model reconstruction, machine learning methods Section 1: Proposing methods for 2D data collection for model training and reconstruction. In this stage we propose a method for analysis, segmentation and annotation of 3D objects on the basis of 2D images for labeling and segmentation. Section 4: The experimental results from the Cham and MySon statues of Vietnam, and the last Section farther is the conclusion and discussion.

2. Related works

In the field of cultural heritage studies, it is necessary to collect images for 3D reconstruction for visual representations and analyze their characteristics. There have been many studies where several ways to achieve this goal have been explored. Authors in [20] analyzed current optical 3D measuring sensors and 3D modeling methodologies, as well as their prospective and actual 3D surveying and modeling of cultural sites. And the ones in [26] presented a novel approach to reconstruct the 3D shape of scene via a single camera.

The paper proposed that it was possible to simultaneously retrieve the structure of dynamic surfaces and static scene geometry in the nature. The study conducted in [4] proposed a method to make it possible for automatically annotating 2D textures of heritage objects and visualizing them onto 3D geometries based on supervised machine learning methods. In a similar context, the authors of [13] presented a method for doing semantic annotations on 2D photos with automated transmission of these annotations between different associated representations of the object (either 2D or 3D).

More recently, works conducted by [15, 21] based on the precise identification and matching of homologous image features, which could be separated into two major parts: image orientation and dense image matching, this method used the camera pose estimation and sparse point cloud generation techniques. However, this approach can still result in a noisy cloud and a number of mistakes. Based on the precise identification and matching of homologous image features, which could be separated into two major parts: image orientation and dense image matching, [25] used the camera pose estimation and sparse point cloud generation techniques. However, this approach can still result in a noisy cloud and a number of mistakes.

The study in [1] performed segmentation incorporating information from both the 3D and 2D space based upon the same mathematical surface. In [12] divided the different components of the building facade without giving the discovered segments semantic names. These authors were concerned with small-scale objects and have a view of a single image. They did not have semantic annotation for models. In [7], the experimental results of the paper involve annotating the 3D model based on feature points from corresponding 2D images. The advantage of the method lies in using a binary mask to filter all the feature points of the 3D model of the same object.

However, the feature points and the binary mask on the 2D images were manually created by the authors. Similarly, in [8], the authors employed a similar idea to semantically annotate the 3D model based on 2D image features. The approach of this paper involves extracting and recognizing features from a pre-recognized and pre-trained model (such as faces) on the 2D images.

The combination of recognition on 2D and 3D models of the objects was limited. We therefore propose an approach for 3D reconstruction, detection, and semantic annotation of a statue based upon information from the 3D model and a set of 2D images. Then, we present an approach to segment objects based upon 2D/3D combination and multimodal approach, working on both 2D and 3D information. This approach detects the information based upon a combination of 2D images and 3D models to detect features in 2D and 3D objects.

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3. Methodology

3.1. Overview

The goal of the proposed method is semantic annotations for 3D objects based on segments of corresponding 2D objects. To do that, we used the machine learning method [5, 22] to train a model, then identify the components that created the 2D object. The data for training here is a set of images collected from many objects and a variety of sources. And to obtain 3D models, with each set of photos of the same object performing 3D model reproduction (helped by [17, 19]), a range of processing data are available).

The important stage of this process is to determine orientation, position and calibrate the set of images to detect the relative orientations and the depth map of the oriented images. Markers linking images are obtained according to SIFT features.

All relations between 2D pixels set and 3D model must be maintained along the reconstruction process. Suppress this and the results of the stage are a semantic segmentation image, which are created from an image segmentation converted into a collection of regions of pixels represented in a labeled image. Thus, the propagation of annotations between images is implemented with a 2D and 3D relative projection. We process only the important segments of the image instead of the entire image Based on the SIFT points, homologous points between pairs of images, direction of images and stage of establishing is the image depth map. The state of model reconstruction combined with image segmented on the same object. The flowchart of our approach is shown in Figure 1.

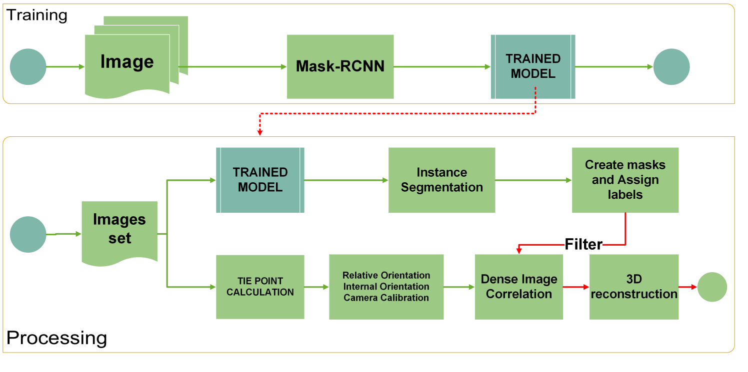

Figure 1. Overview of our processing stages

3.2. Data collection

In the field of 3D model reconstruction from images, to transform 2D image measurements into 3D information, image data needs a mathematical framework. Most of the time, at least two photos are needed to construct 3D data, and projective geometry or perspective techniques can be used [20]. However, in order to improve the efficiency of reconstruction and training, each pair of images needs to have an overlap, and the parameters of the camera such as luminosity, focal length, aperture, and movement speed should be stable [19].

We construct our dataset by digitizing sculptures at the Museum of Cham in DaNang and MySon statues, by taking a set of images around each item. Figure 2 is an example describing a digitization with various camera positions:

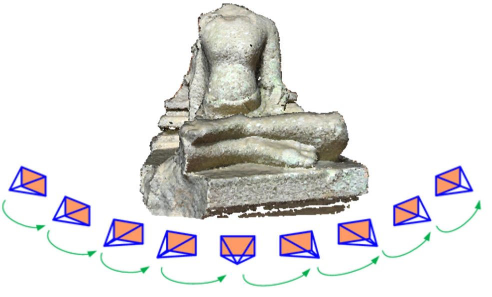

Figure 2. Describing camera positions

With each set of the multi-view images obtained, in the next section we introduce the processing method and reconstruction of 3D model for each set of images.

3.3. Processing and reconstruction of 3D model

In the field of photogrammetry, to calculate depth maps and build 3D dense point clouds, stereo matching techniques are typically utilized in pairs. Through the process of interpolating the 3D sparse point cloud created by the picture orientation process, an initial depth map is essentially produced [25]. This conversion is based on a projection in object space of each pixel of a master image according to the image orientation parameters and the associated depth values. During 3D reconstruction, all images are considered the master image. They are selected and processed in a sequence. In addition, if we want to obtain color features of the object, we just need to choose a master image, the one that can cover the whole object. Each 3D point is associated with an RGB attribute from the master image [18]. In [24] describes a method to recover depth points based on the disparities of corresponding image points and the surface model produced.

Finding a mapping is the goal of matching $\mathcal{F}_{px} : \tau \otimes \varepsilon_{px}$. The point cloud is created in the 3D euclidean space τ. The depth of the Euclidean space is ε_{px} and $\mathcal{Z}$, in there $\mathcal{Z}$ is the image disparity or the Euclid distance between two images. As in Figure 3 and Equation (1).

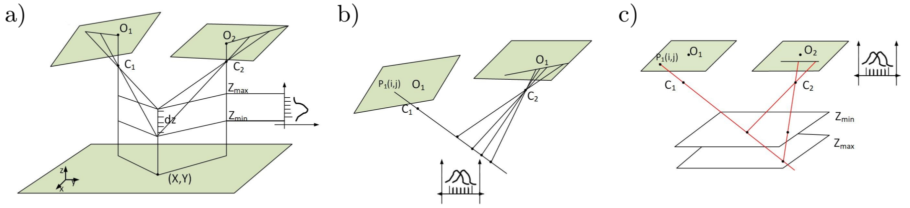

Figure 3. MicMac uses three restitution geometries: a) ground, euclidean space; b) image geometry that is discretized along the ray; c) epipolar geometry resampled in image space

MicMac provides a sufficiently flexible formulation of the matching cost function in terms of the optimization strategy and the dimension of the match.

$$\mathcal{E}(\mathcal{F}_{px}) = \iint_{\mathcal{T}} \mathcal{A}(x, y, \mathcal{F}_{px}(x, y)) + \|\nabla(\mathcal{F}_{px})\|^{reg} \tag{1}$$

The similarity metric between pixels is $\mathcal{A}(x, y, \mathcal{F}_{px}(x, y))$, and $\|\nabla(\mathcal{F}_{px})\|^{reg}$ is the gradient's norm and determined as follows:

$$\|\nabla(\mathcal{F}_{px})\|^{reg} = \alpha_1 * |\nabla\left(\mathcal{F}_{px}{}^1\right)| + \alpha_2 * |\nabla\left(\mathcal{F}_{px}{}^2\right)| \tag{2}$$

In which α_1, α_2 are the regularization of the disparity's first and second elements, respectfully. The a priori in the disparity space is controlled by value of $\|\nabla(\mathcal{F}_{px})\|^{reg}$. Micmac used a global reduction using the Min-Cut/Max-Flow approach to identify the disparity map that optimizes the energy [23]. This stage provides a map of correlation coefficients between pairs of images to determine the depth for each pixel in the depth map. Each 3D point, after reconstruction, is always associated with a specific pixel. The main processing steps on the stage of reconstruction [10, 16, 19] are described as follows (see Fig. 4):

1. Take pictures from different positions and directions to cover the entire subject.
2. Calculate tie points and the match between all pairs of image using the SIFT algorithm.
3. Use the tie point set of observations in the bundle adjustment and determines the element of image orientation (external orientation and camera calibration).
4. Use orientation of image to measure the likelihood for pixels from two images to belong to a unique three-dimensional point. And the image dense matching performed in the image's geometry with the pair image. As a result, one depth map is generated for each image. These depth maps are merged into one single point cloud model covering the entire area.
5. Finally, extract the global point set by using an energetic approach to minimize, on the whole considered space, a sum made up of correlation coefficients for each pair of images and smoothing term in order to homogenize the point set.

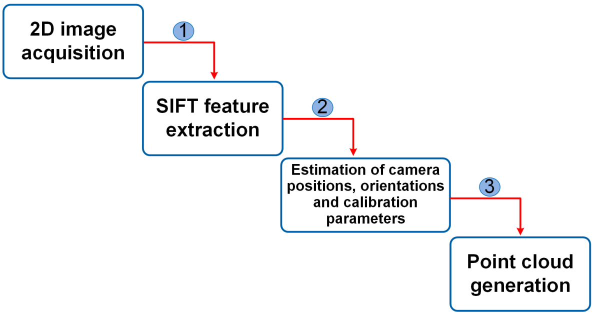

Figure 4. Overview of point cloud generation process

In this stage, key points (interest points) are detected from image, then the key points are computed for descriptors by Sift algorithm. By comparing the two sets of stereo image descriptors, they will be matched to obtain corresponding points. The point matches will be utilized to calibrate and align the photos in 3D coordinates, as well as to acquire camera views automatically. Additionally, a well-known method called RANDOM SAmple Consensus (RANSAC) is utilized to eliminate outliers, or unreliable point matches, depending on camera settings. A bundle adjustment used to compute the camera parameters is referred to [17].

Depth map merging: The multiple depth maps that focus on the same area of the image are combined to eliminate the duplicate depth values for each back-projected 3D point and project to the 3D space. This results in a smooth and distinctive thick cloud. While in the process of fusing, similar to the depth filtering step before it, pixels are once again projected to the three dimensional space and then back projected to the neighboring views, merging only the depth values that are determined to be close enough [25].

3.4. Semantic segmentation and annotation on 2D image

Convolutional Neural Networks (CNNs) are a type of deep learning algorithm highly effective for visual data analysis. Designed to process pixel data, CNNs excel in tasks like image classification, object detection, and image segmentation by learning spatial hierarchies of features through layers such as convolution, pooling, and fully connected layers.

Convolutional neural networks are one of the most advanced models, having been widely used in the deep learning method. From the research results of CNNs, there have been many applications using the research results in the identification and image classification. The paper uses the identification and segmentation results to annotate corresponding 3D object models. Figure 5 presents the process using machine learning [5, 22] on our dataset, for identification and image classification. The proposed method includes the following main stages: The first stage is to generate a set of proposals candidate object bounding boxes that have the higher probability of an object called a Region Proposal Network (RPN). The second stage extracts features using these proposals from each candidate box, performs classification and bounding-box regression. And the third stage presents mask segmentation on each Region of Interest (RoI) as Figure 5.

1. Use convolutional neural networks to extract input features.
2. Characteristic zones are routed through RPN to find RoIs and return them to bounding boxes in zones containing objects.
3. The RoIs are separated from the feature map and through the RoI pooling layer to adjust and stack into blocks on the same size.
4. The RoIs are passed through the connection layer for classification and boundary box prediction.
5. In step 3, RoI continue to be processed through 2 convolutional steps to create binary masks for objects.

From the method, we have gained a model, after training, for object identification and segmentation. Hereby, we propose a method of separating zones which have been identified, to mark and label different parts, respectively, for each image in the dataset. The purpose of reuse in the filter extraction of specific zone and establish a depth map for each image in section 3.4 and mark, label the 3D point set to create semantic annotations for the objects.

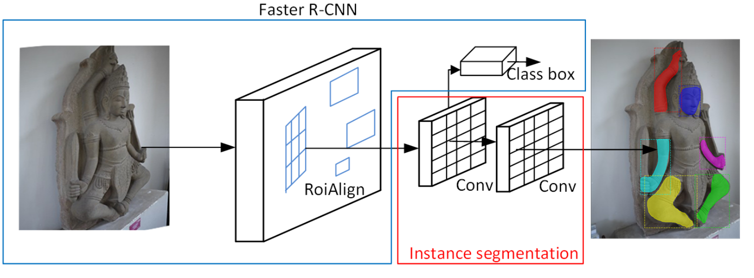

Figure 5. The architecture of the Mask-RCNN model used to segment for one point of view

In the training step, authors [22] defined a loss function on each sampled RoI as:

$$L = L_{cls} + L_{box} + L_{mask} \tag{3}$$

Where, the classification loss $L_{cls}(u, p) = log(p_u)$ is the log loss for each class u with network predicted probability p. The box loss L_{box} is defined over a tuple of true bounding box regression targets and the center of box, dimensions for class u, $v = (v_x, v_y, v_w, v_h)$, and a predicted tuple $t_u = (t_x^u, t_y^u, t_w^u, t_h^u)$, for class u is:

$$L_{box} = \sum_{\in x,y,w,h} smooth_{L_1}(t_i^u - v_i) \tag{4}$$

in which:

$$smooth_{L_1}(x) = \begin{cases} 0.5x^2, & if|x| < 1 \\ |x| - 0.5, & otherwise \end{cases} \tag{5}$$

L_{mask} is defined as the average binary cross entropy loss:

$$L_{mask} = -(ylog(p) + (1 - y)log(1 - p)) \tag{6}$$

After performing the model training, the segment results of some statues will be shown in Figure 6. Thereby, each segmented image will be processed to attach a corresponding label and ID. For the same segment type, the same label will be used. As the Figure 7 shows, although the images have different shooting directions, if the part of the head, arms and legs are the same, they will all have the same label.

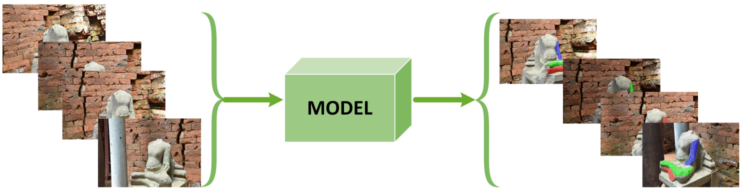

Figure 6. Using pre-trained models for annotation and segmentation

The aim of this step is to build an instance segmentation model for cultural heritage items segmentation by fine-tuning the state of the art Mask-RCNN algorithm. The model is performed using heritage dataset which is prepared and collected from Vietnamese statues.

3.5. Multi-modal merging step : automatic indexing 3D points sets

The 3D model obtained from one point of view after reconstruction is an unstructured of points and its information is discrete. However, the 3D points that are characterized are obtained from the feature sets, and each point is added with depth information. From that results, our method annotates the 3D object based on the identified and segmented set of images. Based on the masking of the segmented images to mark and filter the corresponding 3D point cloud, with each segmented part the creation of a 3D mask, labeling and indexing 3D points.

The sequential steps are described as follows:

1. Using the trained model to segment each image, set corresponding labels for each segmented part. Each segmented part must contain pixels with a different color and classes.
2. For each segmented image, we need to extract information as orientation, position and depth map that have been created in the reconstruction step.
3. Create a binary mask and apply corresponding labels to each segmented part.
4. Based on the depth map of each image, create the sub 3D point cloud and the corresponding binary mask to extract the set of 3D points for each segmented part.
5. Each obtained 3D point set for each segment part on the same label is merged.

In this step 4, the images are oriented in relation to each other, and the depth map of each image created. Each depth map is converted into a 3D, metric point cloud by projecting each pixel of the image in space according to the image orientation parameters and pixel depth by [24] and method [7, 11], based on the binary mask, to extract the set of pixel depth for each mask part according to the segmented composition. With each data set collected, we perform the model reconstruction to obtain 3D point cloud. As shown in Figure 7, the results on some models will have 3 different perspectives after reconstructing.

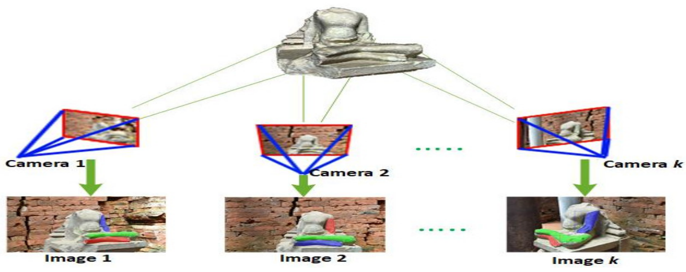

Figure 7. Annotation 3D model based on segmentation and orientation of the corresponding images

In Figure 7 one can see the generation of a point cloud for a segment, we made: For each image of the dataset segmented and labeled has similar labels, then group together (as arm, legs, face and so on). These segments have the same label mapped to 3D point cloud based on extracting the depth map corresponding to each part. Finally, merge all subset of point cloud with the same label. Because all the generating point clouds are in the same reference system, they can be easily mixed together, based on the position and orientation of segmented image and the depth images created point cloud. As described in section 3.3, these images used in the steps for the point cloud generation. It has an oriented, defined position in the MicMac tool chain. Figures 8 and 9 present 3D segments which are annotated and merged on one image.

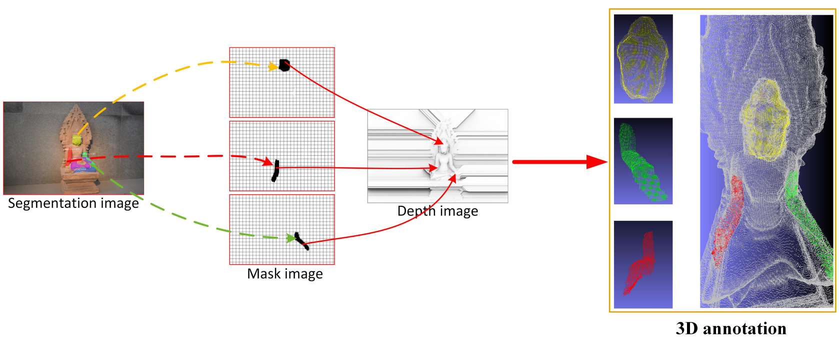

Figure 8. Use the mask of one segmented images to filter the corresponding 3D point cloud

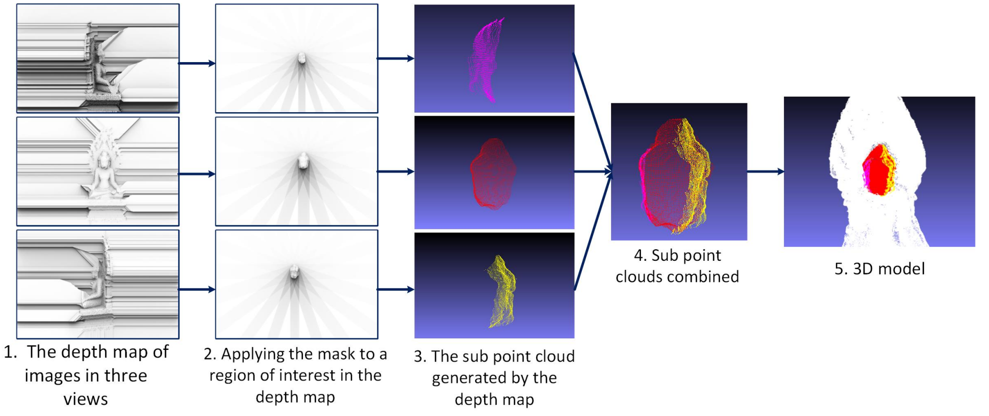

Figure 9. The example of depth map in 3D view and the merged point cloud

4. Experimental results

The image dataset used for training stage were obtained from heritage objects in museum of Vietnam such as Da Nang, MySon. The sample images are summarized in Figure 10, but they do not consist of the number of acquired images. The images are also used for 3D modeling obtained from heritage objects such as sculpture, statue. To provide data for training the CNN network for automatic semantic segmentation, the data labeling was done manually. The labeled images include five classes sharing certain similarities, namely “left hand”, “right hand”, “leg right”, “leg right”, “face”. We train the statue model architecture with backbone CNNs namely ResNet-101 and using our own dataset to fine-tune all layers directly on the pre-trained weights obtained from MSCOCO dataset [5, 9].

As Figure 10 shows, various patterns of images were obtained from Champa museum for various statue type Shiva lingam, Garuda, Visnu, Tusi, Myson, Nuthan, Linhvat.

The Figure 11 shows training and validation loss value and the Region Proposal Network loss value while training one of the segmentation models.

Figures 12, 13 and 14 show the results of the instance segmentation framework on sample statues. Our research results are also limited by training and evaluation elements to arms, legs, face of the statue. The next step will be: given each set of 2D multi view images, 3D model is reconstructed and represented with texture. With the [24] method, we can obtain a 3D model from the set of images taken around the object from the featured point set analysis of the image and use the geometric model to reconstruct the model. All relations between 2D pixels set and 3D model must be maintained along the reconstruction process. The sample images and 3D model of Cham statue are shown in Figures 16 and 15.

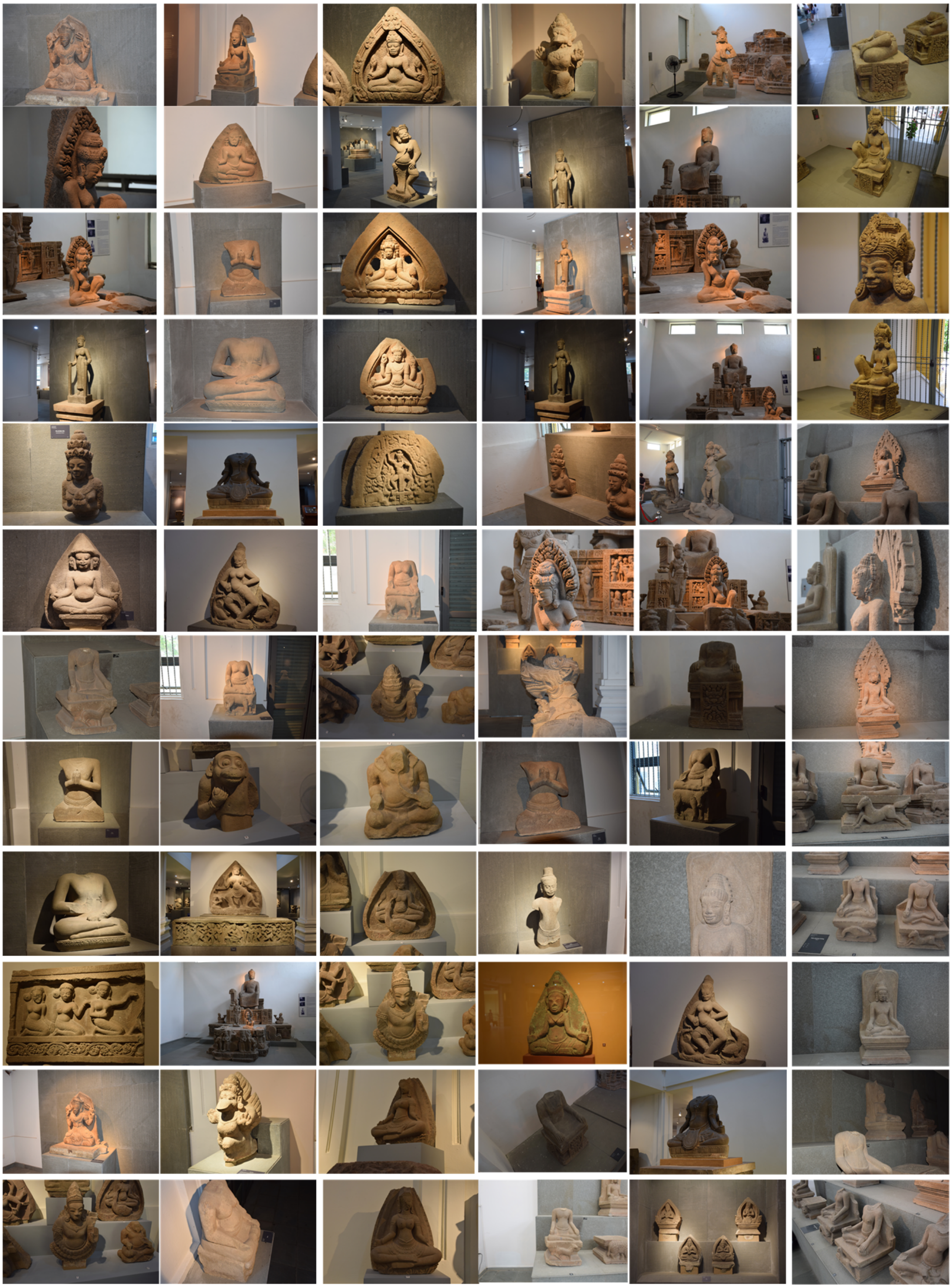

Figure 10. The training 72 sample images

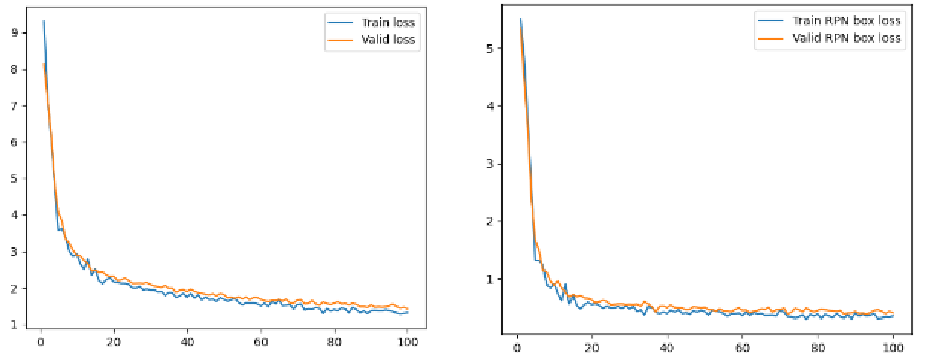

Figure 11. Training set loss (blue) and validation set loss(red) per epoch during the training epochs

Figure 12. Segmentation images with MySon statue

Figure 13. Segmentation images with Nuthan statue

Figure 14. Segmentation images with Champa

Figure 15. 3D point cloud of Cham statue with texture

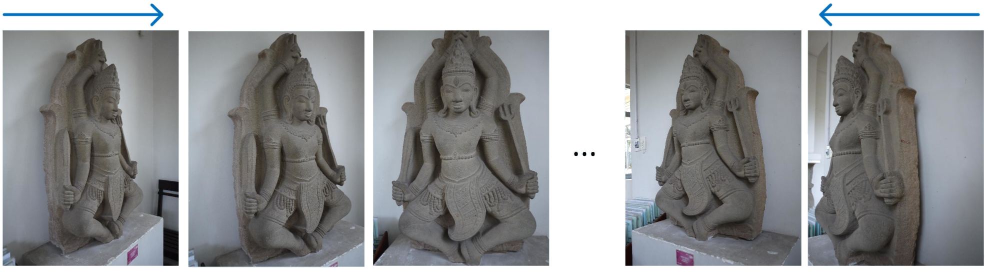

Figure 16. 2D multi-view images of Cham statue

Another sample images and 3D point cloud of Myson statue are shown in Figure 17 and 18. And sample images and 3D point cloud of Nuthan statue are shown in Figure 19 and 20.

Figure 17. 2D multi-view images of MySon statue

Figure 18. 3D point cloud of MySon statue with texture

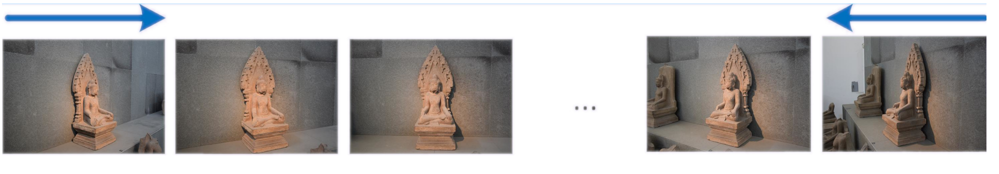

Figure 19. 2D multi-view images of Nuthan statue

Figure 20. 3D point cloud of Nuthan statue with texture

As mentioned at Section 3.4, we trained the network with batches of size 50, a learning rate $\alpha = 2.5 \cdot 10^3$ over 100 epochs and the training data comprises an image set of cultural heritage. For the loss function, we used the binary cross entropy, which is defined as 3. As Figure 11 is an illustration to record the results of training set loss and validation set loss per epoch during the training epochs.

In previous processing step, 3D point clouds were created by using MicMac tool chain. Feature detection and feature matching were the key concepts to produce 3D point cloud from an image sequence. Figures 18, 15, 20, are showing the point cloud model of the statue. From the results, we see that the raw point clouds are often noisy and have holes, because it depends on the image acquisition technique as they represent the input data. So, the context must be exhaustively analyzed, including the lighting conditions of the scene, the values of exposure aperture and shutter speed of the camera.

Also in this period, we used [5] method to detect the part of statue as face, hands, legs on the 2D image, and from these the segmented image extraction is converted to binary mask to create an annotation area on point cloud, the 3D mask is created by a 2D binary mask. So, a white pixel coordinates will be extracted from the associated corresponding point cloud. And each point cloud set of different image orientations, after reconstructing, obtains a point cloud set of the same method [24]. So they all maintain the same scale and resolution, the combination between them are done by MeshLab open source software. Each point cloud is labeled with the annotated 2D image label.

The obtained results are shown on Figures 21, 22 and 23, the left image creates 3D semantic annotations. The middle images and right image shown with non-texture and texture of the point cloud.

The experimental results demonstrate that the method achieves more detailed effectiveness in recognition, segmentation, and semantic labeling compared to previous studies. For instance, in [7], manually segmenting and identifying features in images posed limitations due to the requirement for manual region creation. Conversely, [8] employed a pre-trained model to identify parts of object faces. Our approach involves data collection, model training, and segmentation recognition on 2D images, followed by semantic labeling applied to corresponding 3D point clouds. However, the efficacy of identifying regions and features heavily relies on the quality of training data. The method also faces limitations, such as unclear areas in 2D datasets posing challenges during labeling. Regarding point clouds, the quality of 3D model reconstruction depends on the quality of collected image data, with a risk of increased noise levels in low-quality data.

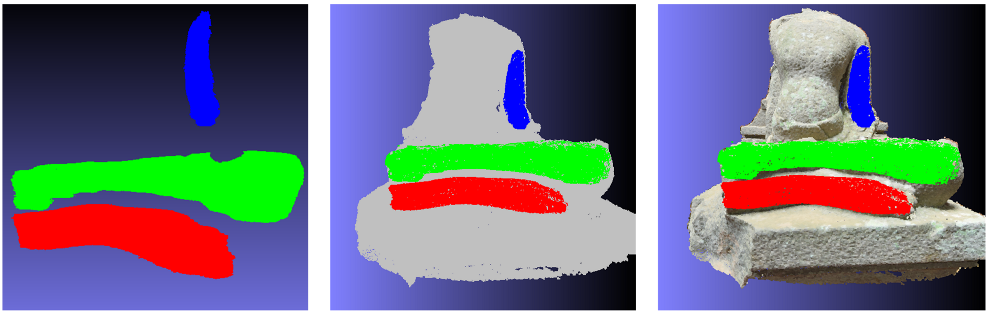

Figure 21. 3D indexed parts of point cloud of MySon statue

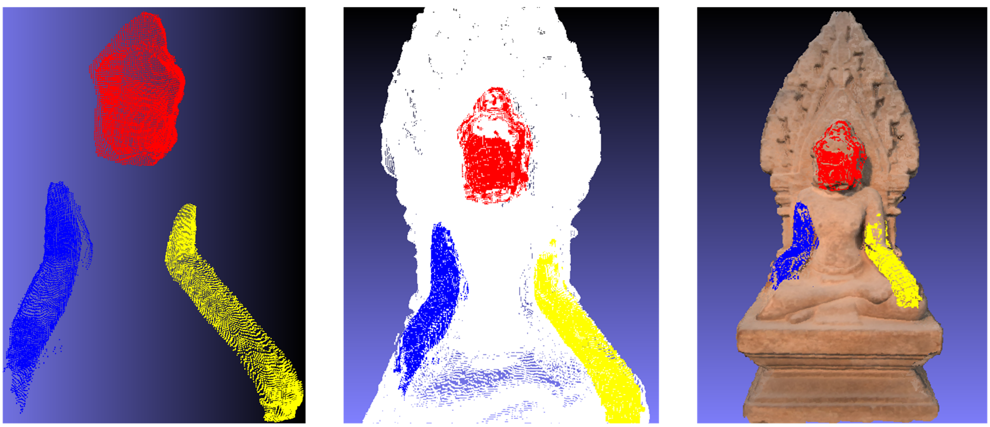

Figure 22. 3D indexed parts of point cloud of Nuthan statue

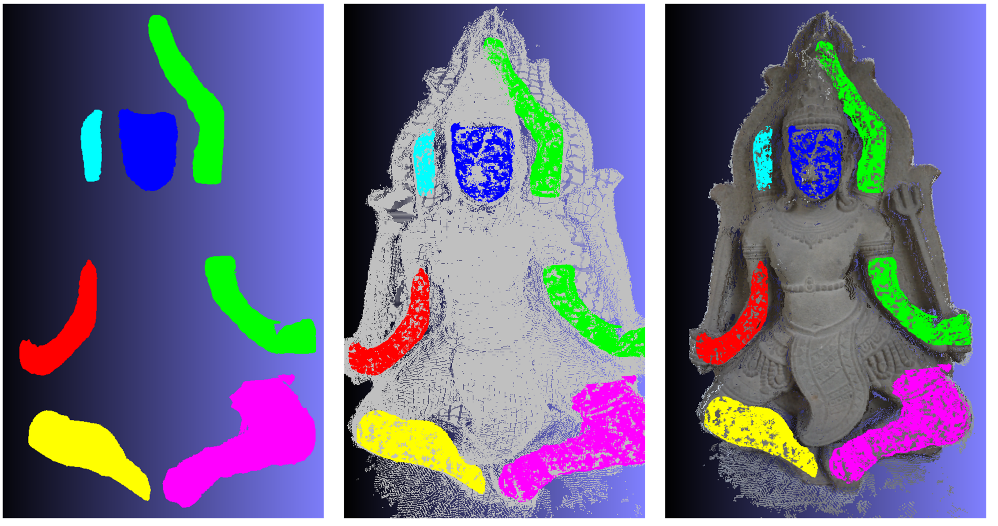

Figure 23. 3D indexed parts of point cloud of Nuthan statue

5. Conclusion and discussion

The process of reconstructing 3D from 2D images compared to digitizing 3D objects by focusing on collecting 3D points presents both advantages and challenges. While reconstructing from 2D images is often more feasible and convenient, it also faces challenges regarding accuracy and detail. Despite occasionally not achieving high precision, this method offers flexibility and lower costs, thus fostering potential development in cultural heritage preservation and research. The outcomes of the paper involve collecting and reconstructing images of several ancient sculptures at the Da Nang Museum and the My Son relics in Vietnam. Test results provide a foundation for segmenting, identifying, and analyzing various parts of 2D/3D objects for digital storage and preservation. With the proposed method, initial results include reconstructing and identifying parts of sculptures such as heads, hands, and feet. The paper‘s future research direction aims to identify all other components comprising the objects, creating a dataset of related parts for research and reconstructing damaged 3D models. In the future, we will propose reconstructing 3D models to identify and analyze damaged models, leading to their complete reconstruction. This will serve as a foundation for restoring ancient models and providing a database for research and preservation. We will reconstruct 3D models of various archaeological sculptures in Vietnam, potentially providing public access through a website and establishing a web-based annotation system. Highly accurate 3D models can serve as reference data for heritage, archaeological objects requiring restoration due to aging or natural disasters.

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PERFORMANCE EVALUATION OF A LIGHTWEIGHT CONSENSUS PROTOCOL FOR BLOCKCHAIN IN IoT NETWORKS

Abstract *The consensus protocol is essential in practically every blockchain application. Most of these existing blockchain consensus protocols need massive computational capabilities, substantial energy consumption, and dependency on monetary stakes. These shortcomings in the mainstream consensus approach lead to their unsuitability for low-resource applications like IoT. As a result of this work, a lightweight consensus process referred as Delegated Proof of Accessibility (DPoAC) is implemented and evaluated. DPoAC makes use of Shamir secret sharing, Proof of Stake (PoS) with random selection, and the Inter-Planetary File System (IPFS). The DPoAC operation is composed of four modules: secret generation and distribution, retrieval of secret shares, block creation and verification, and block rewards and penalty. A detailed description of DPoAC has been provided and implemented in JavaScript and experimental results demonstrate that our solution meets the necessary performance and security requirements for a lightweight scalable protocol for IoT systems.*

Keywords blockchain, consensus protocols, DPoAC, secret sharing, IPFS, IoT

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1. Introduction

Blockchain is made up of a number of interconnected blocks that hold an extensive list of transactional information, much like a conventional ledger. The use of cryptographic hash algorithms to store records in these blocks is a notable characteristic that distinguishes blockchain from other traditional approaches. Blockchain is a decentralized public database that groups cryptographically signed transactions into blocks [20]. Following validation and consensus, every block is connected to the block before it to make it temper-proof. As new blocks are added to the blockchain, it becomes progressively harder to change the earlier ones. When a new block is inserted into the blockchain, a broadcast is made to the network to update the local copies of the blockchain retained by the participating nodes [14, 27]. Blockchain offers trust in two-fold. First, the committed transaction records are immutable due to the block-linking method, ensuring that the data in the chain cannot be altered. Secondly, the reliability of the data being entered into the system by P2P nodes is governed by the consensus process. Every piece of information must get the consent of a majority of participants to get included in a block, as guaranteed by consensus [11]. Being a distributed structure, blockchain maintains the integrity of data blocks using consensus protocol. In the past various consensus, algorithms have been developed and deployed in specific applications. Unfortunately, no such algorithm is without flaws. Most contemporary blockchain systems are unable to meet the requirements of any substantial real-world application because of severe restrictions set by privacy, security, and throughput. Many of these limitations are the consequence of difficulties that arise as an outcome of underlying consensus. Hence, consensus methods have played a significant role in the creation of more useful blockchain networks [13, 16].

Proof of Work (PoW), Proof of Stake (PoS), Proof of Activity (PoA), and Delegated Proof of Stake (DPoS) are well-known consensus techniques that have been studied thoroughly in the blockchain domain by researchers [16, 18]. PoW forces participants to resolve a complex computing problem, to increase the difficulty and cost of the process [16]. Many PoW variants have been adopted, including PoS, which requires that a node must deposit a certain quantity of coins in order to be granted block creation privileges [16, 18]. Hence, a node with a high stake is more likely to gain block creation privileges over the other nodes with relatively low stakes [16].

Other variations, such as DPoS and PoA, exist in relation to these widely used consensus methods. DPoS outperforms PoS in terms of efficiency and speed [16]. A group of nodes are chosen to serve as delegates in the network through an election process including stakeholders. These delegators will produce new blocks based on a predefined sequence, and a delegate will be eliminated if it does not produce a block in its turn [16]. DPoS is a more affordable and powerful consensus method than PoW and PoS [16, 18]. Unfortunately, voting could not prevent malicious entities from being selected, especially in small networks, and may pose certain security risks. Miners may typically lose interest in the mining process as the bitcoin reward is reduced by half after every 210,000 blocks mined. As a result, miners will demand a hefty transaction fee for the computational resources used in the mining process. As a result, a hybrid solution known as Proof of Activity (PoA) has been devised, which is a combination of PoW and PoS. As this approach is hybrid in nature, it is more complex to implement and demands heavy computations due to the inclusion of PoW [16].

IoT applications have evolved over time and impose a significant impact on our day-to-day lives. However, with the rapid growth in the deployment of IoT systems, severe issues in the context of scalability and security have been uncovered. The processing power and computational capabilities of current IoT devices are limited. Blockchain technology may be considered as an optimal solution for supplementing these limitations of IoT devices. Blockchain, being a decentralized architecture, reduces the likelihood of center point failure and increases security [16]. Scalability would be increased since data is spread across the network instead of being retained on a single server. The current mainstream consensus approaches, on the other hand, have substantial drawbacks, such as low efficiency, huge power consumption, and increased resource demands. Blockchain applications are impractical due to these limitations, particularly in the IoT/IIoT ecosystem [16, 17]. Due to its significant resource requirements, PoW is particularly unsuitable for resource-constrained applications such as IoT/IIoT [16]. The main barrier preventing PoS approach from being used in IoT networks is the requirement of a stake in cryptocurrency terms, which is irrelevant in IoT networks [7, 11]. Similarly, the key limitation of DPoS in IoT contexts is its dependence on financial stakes to choose delegates [16, 24]. Although the PoA technique is less susceptible to malicious threats, prolonged latencies may arise, that might be undesirable for time-critical IoT applications [6, 16].

These concerns lead us to create a new consensus mechanism that inherits the benefits of existing consensus methods and addresses their shortcomings, particularly in IoT. Therefore, through this paper, we implement Delegated Proof of Accessibility (DPoAC), a new consensus protocol that combines two distinct strategies, namely Proof of Accessibility and Proof of Stake with Randomized Selection. By combining the characteristics of traditional Proof of Accuracy and PoS algorithms with modifications, DPoAC builds on the idea of a hybrid algorithm. Proof-of-accuracy consensus techniques have received minimal research in past. The Proof of Accuracy Protocol [19] selects a coordinator, generates a secret, and distributes it across multiple nodes by separating it into secret components. The willing nodes must compete for access to those nodes in order to acquire the secret components and rebuild the secret. The node that has acquired the capacity to regenerate secrets will be designated as the block generator for new blocks. This study was mostly conceptual, with no practical implementations. The key contributions of this paper are mentioned below.

Although the paper [25] introduced the idea of DPoAC, no specific implementation was provided; only a qualitative analysis was included. Through this work, we have provided comprehensive algorithms to demonstrate the operation of DPoAC.

We implemented the DPoAC protocol and assessed its performance quantitatively against the comprehensive performance matrix. In terms of scalability, security, fault tolerance, overhead, and latency, DPoAC outperforms mainstream consensus protocols.

Paper structure

The remainder of the paper is arranged as below. Section 2 discusses the background and related works. The detailed description and operation of DPoAC are included in Section 3. Section 4 evaluates the performance and provides a performance comparison of DPoAC. At last, Section 5 concludes this research article and outlines future work.

2. Background and related work

2.1. Shamir Secret Sharing (SSS) Scheme

The SSS technique is a distributed method of preserving secrets, particularly cryptographic keys. A secret is divided into many portions called shares [16]. These individual shares are used to piece together the original secret again. A fixed number of shares are necessary to discover the secret using SSS. The threshold represents the minimal amount of shares necessary to disclose the secret [10, 16]. To further comprehend the SSS scheme, consider a secret S that has been broken into n different portions, $S = S_1, S_2, ...S_n$ in a way that satisfy following requirements [16, 25]:

- To regenerate the original secret S the information of a minimum of k distinct secret portions are necessary.
- The information of only $k - 1$ or fewer secret portions cannot determine S.

This approach is known as the (k, n)-threshold scheme because it requires just k data pieces from total n to recover the original secret.

2.2. IPFS

IPFS (Inter-Planetary File System) is a peer-to-peer distributed file system that could be employed instead of HTTP [5, 16]. Unlike HTTP, IPFS employs content-based indexing; when a file is included in the system, it is divided into 256-byte chunks. These chunks include object data and linkages that will be preserved in a Merkel DAG [15]. The system offers one hash value termed as the basic content identifier (CID) [16] to obtain the file from IPFS. The Distributed Hash Table (DHT) is used on IPFS to store information; the distributed option enables the latest hash tables to be made accessible across many places [3, 16]. DHTs are generally used to record and retain information in P2P networks. It is a decentralized solution that uses a hash table-like lookup structure to retain index-value pairs, and users may efficiently access the content associated with a certain index. DHT supports content discovery, network routing, and peer discovery in IPFS [16]. The content-based indexing employed in IPFS makes it a more accessible and stable option for integrating with the blockchain.

2.3. Blockchain-IoT integration

The IoT primarily consists of hardware components, gateways, fog/edge nodes, clouds, and the internet. IoT enables edge devices and Cloud platforms to understand and store data by allowing physical entities to broadcast data over a gateway [7]. These devices could follow instructions to perform a specific behavior from one another over the Cloud. A central manager for the Cloud may also issue commands. The IoT stack and standard protocols collaborate to offer architectural layers that provide services to hardware objects in the IoT network. Currently, centralized architecture is used in the vast majority of IoT solutions [7]. But IoT systems suffer major limitations due to the reliance on central servers. The heterogeneity of IoT devices in use presents a number of difficulties in the context of security, privacy, and interoperability. Furthermore, as more devices are added to an IoT system, network management becomes more complicated, resulting in poor scalability. Server failure, resource- constraint nature of IoT devices, privacy concerns and large-scale data management are some other challenges that draw attention while considering IoT applications. Blockchain offers a P2P network where all network devices share memory and computational resources. The cost of establishing and maintaining clouds, data centers, and networking hardware could thereby reduce. Distributed communication architecture can help solve the problem of a single point of failure [16, 22]. As a significant component of blockchain, cryptographic algorithms enable this framework to have intrinsic security and privacy protections in IoT networks. Additionally, blockchain is able to address problems with data integrity brought on by IoT devices since distributed ledgers are irreversible in nature [4, 16, 17]. Despite the fact that blockchain has built-in security, data integrity, and a lack of central authority, implementing blockchain in resource-constrained IoT networks is exceedingly difficult due to inefficient consensus mechanism, big data storage and high througput needs of IoT systems [16, 17].

Kudin et al. [19] suggested Proof of Accuracy (PoAc) as a theoretical concept only. PoAc relies on evidence of access to the input data required to solve the given problem as well as the provision of a solution to a problem with a certain computational complexity threshold. Practical specifications were not provided; only a theoretical concept was conveyed.

Naz et al. [23] introduced an IPFS-based data-sharing and digital asset-distributed platform using blockchain. This solution increases security and access control by performing authorization operations through a smart contract written by the owner. The suggested solution was implemented on an Ethereum private blockchain. Due to the encryption imposed by the Shamir Secret Sharing algorithm used to hash IPFS data hashes, clients with pending debts for online content have been prohibited from data access. This protects the owner from any unauthorized access to the hash. Users may be able to search for and publish reviews using the smart contract-based review system. Results from simulations have been used to assess the economic feasibility and energy usage of the introduced system.

Zhang et al. [28] proposed a unique hierarchical threshold secret-sharing strategy based on blockchain technology. The secret is available to any approved subgroup of system users, and private shares are spread across various levels of system users. Smart contracts were developed to identify illegal actions and secure the integrity of the secret-sharing mechanism. If users do not honestly follow the regulations, dishonest conduct may be uncovered, resulting in a financial penalty. Finally, participants may duplicate the secret fairly despite the lack of a central authority.

Liang et al. [21] created a secret-based robust data transportation system based on SSS to transfer data across trade centers with the help of secret sharing. Data is stored in a flexible, connected storage system using a consensus approach. Unfortunately, this technique was meant for specific applications, and the importance of power data security was overlooked.

There are various vulnerabilities that can harm online data housed on a central system controlled by a single party. Masayuki et al. [8] presented secure storage that does not require a central server. Unauthorized access to private information has been prevented. The information of each user has been segmented using a hidden sharing scheme. These portions are stored on separate network nodes. By obscuring the most crucial properties of data, it is converted into metadata. By exploring for nodes in the network that hold the data segments, a user may reconstruct the original data. This proposed method was reliable since it enables a user to find desired data even though the network architecture changes. Furthermore, other nodes in the network may discover a fraudulent node via majority rule consensus. But there was no quantitative evaluation of system security.

Geng et al. [9] introduced an improved consensus approach for a broad blockchain network that incorporates a verified secret-sharing technique. Verifiable secret sharing protects privacy, and secure multi-party computing was used to boost privacy, effectiveness, and equality.

Zhou et al. [29] investigated the privacy-protection aspects related to permissioned blockchain in the context of multi-party computing. In this effort, a secure MPC protocol was incorporated into Hyperledger Fabric. Secret sharing, homomorphic encryption, and zero-knowledge proof were all used in the proposed protocol.

Andrian et al. [1] demonstrated how IPFS may be used to increase accessibility and efficiency by sharing data across multiple IPFS nodes. The rate of data flow and status for nodes are provided through a real-time monitoring system. Experimental results showed that the IPFS-based system speeds up throughput and minimizes file replication time when compared to the performance of the existing version.

Aponte-Novoa et al. [2] developed a detailed design and implementation of proof-of-accuracy consensus through this work. To control miner computer power and minimize majority threats, authors focused on democratizing miner involvement in a blockchain. The suggested system has provided the results of simulations conducted in Python.

Ullah et al. [26] developed an IoTChain model by employing IPFS, Ethereum, AES encryption scheme, and Proof of Authority (PoA) consensus mechanism. To store data produced by IoT devices IPFS based blockchain-enabled system was designed. The simulation results were analyzed to examine the performance and transaction expenses.

Kara et al. [12] introduced a novel Proof of Chance (PoCh) consensus method that reduced the need for extensive resources in the mining process. The algorithm chooses a block producer depending on the value of the chance parameter and the target value. The performance of PoCh against different criteria in the IIoT context was supported by the experimental findings.

3. Proposed consensus protocol

Consensus protocol as a vital element of any blockchain application is influenced by a number of threats including huge resource needs and energy usage which restricts the deployment of blockchain in several domains. Due to restricted resources, IoT/IIoT applications cannot employ these high-cost consensus procedures. Delegated Proof of Accessibility (DPoAC) is therefore offered as a novel consensus process that employs the Shamir secret sharing approach, modified PoS with random selection, and IPFS. DPoAC operates in two phases. P2P nodes are sorted according to their accumulated reputation stake. During the early phase, one node is selected randomly among the top P2P nodes as a super node for each round. A secret is generated and divided into n shares by a randomly selected super-node. These shares are encrypted using the RSA encryption algorithm and saved on distinguished IPFS nodes. To reassemble the secret, the nodes will contend for access to these shareholders. The winning node will receive block-generating rights. The appropriate hash value is calculated and a block with legitimate transactions is built in the second phase using modified PoS with random selection. A node holding a high currency stake can win mining privileges over other nodes with a smaller stake in a conventional PoS system. But the stake in currency terms is not applicable for IoT nodes therefore we replaced this monetary stake with the reputation stake. In this customized approach, a node has to prove its reputational stake to the super node in order to secure block creation rights. Moreover, for every successful mining, the winner node is entitled to reputation coins that would increase its likelihood to gain block generation privileges and even the chance to become a super node for future blocks. With this innovative approach, a node with little computing capabilities and minimal monetary stake may still secure block generation rights by demonstrating access to secret shares and reconstructing the secret, which makes the system relatively equitable [16].

3.1. Design of DPoAC

DPoAC design consists of five basic entities, and the DPoAC process is divided into four modules explained below. A list of abbreviations used in various algorithms is shown in Table 1.

Table 1
List of abbreviations and notations

Symbol	Description
F_p	A finite field of integer modulo p
$p, p_1, p_2 \in N$	Prime numbers
n	Number of secret shares
k	Threshold shares
S	Secret generated
$i, j \in N$	Identifiers
$S_1, S_2, ...S_n$	Secret shares
$S_{1e}, S_{2e}, ...S_{ne}$	Encrypted shares
H(S)	Hash value of secret S
CID_i	Content ID for i^{th} secret share

3.1.1. Entities

1. Delegated Super Node: It is a node with a specified reputation stake that is chosen at random out of a group of delegates to begin the process of granting block generation permissions to other nodes [16].
2. P2P Nodes: It is a node in a peer-to-peer network that maintains a private-public key pair as well as extra metadata [16].
3. Miner Nodes: A node with particular interests and capacity to reveal the secret number created by the authorized super node within a certain time frame [16].
4. Secret Shareholders: These peer-to-peer (P2P) nodes will be employed to keep the system's secret shares and will be obliged to release these shares at the demand of peers who have been proven to be authentic [16].
5. Forger Node: This is the winner node, which has successfully reproduced the secret and is entitled to block creation privileges [16].

3.1.2. Modules

1. Secret Generation and Distribution [16]: A delegated super node generates a random secret number S, and its hash, which is concealed from P2P participants, is computed as $H(S)$ and preserved using a (k, n)-threshold cryptographic scheme such as Shamir secret sharing protocol. After then, the secret S needs to be divided into n shares or partitions. Following encryption, those shares, together with any accompanying metadata, are recorded on diverse stakeholders via the IPFS protocol. $H(S)$ will be sent to all other nodes.
2. Secret Shares Retrieval [16]: To reveal this secret, at least k shares out of n must be collected. Therefore, miner nodes make contact with IPFS nodes that hold the secret shares. The first node which has successfully retrieved and accumulated k shares will divulge and prove this secret to the delegated super node. By comparing the revealed secret to $H(S)$, the remaining nodes may easily certify that secret shares had been accessed and the correct secret had been regenerated.

3. Block Creation and Verification [16]: A node will be given the ability to create blocks after it has demonstrated that it has gained access to all shareholders and disclosed the exact secret created by the super node. We refer to this node as a "forger node" at this point. Using its secret key, the forger must compute an encrypted value from the hash of the preceding block. This encrypted data is then hashed, and the first 64 bits of the resulting hash are referred to as the "hit value". The inclusion of a secret key in the preceding computation ensures that a forger obtains a distinct hit value. Forging is assigned to a node that returns a "hit value" smaller than a "target value" [18]. The target value is calculated using Equation (1).

$$Target\,value = T_b \cdot L \cdot R_e \tag{1}$$

   where T_b = "base target value" = preceding block target value, L = the amount of time consumed by the last block, R_e = total reputation coins accumulated or staked [16, 18]. When a block is created, it must be sent to all P2P nodes for confirmation. If greater than 50% of the nodes in the network confirm the block, it will be included in the blockchain [16].
4. Block Rewards and Penalty [16]: If a forger successfully constructs a block that is accepted by a large number of P2P nodes, both the forger and the super node get compensated with reputation coins in an 80:20 ratio. However, if a forger tries to make a false block, the staked reputation coins are lost, and the forger is required to wait a certain period of time before participating in the next block formation round. This method will keep the system safe from malicious attacks.

3.2. Working of DPoAC

When there are transactions in the transaction pool, a super node is randomly selected from the list of delegators. Using the Shamir secret sharing mechanism, a chosen super node will generate the secret number S. The hash value for this secret number will then be computed by the super node and stored as $H(S)$ [16]. The process of secret generation and reconstruction is shown in Figure 1.

Algorithm 1 demonstrates the detailed process of the generation of secret shares and $H(S)$. We utilized IPFS to store and access these shares, and IPFS is based on content addressing, so anyone with a given CID (Content Identifier) may access the data. However, any node with a CID can access the data but not modify it since minor changes in the data would result in a new CID (data de-duplication). Transport encryption is provided by IPFS as an intrinsic feature to prevent third-party/malicious user eavesdropping when data is being transported from one node to another. However, content encryption is missing that secures the data even if it has been accessed by fraudulent users. Therefore, content encryption is essential before storing the data on IPFS.

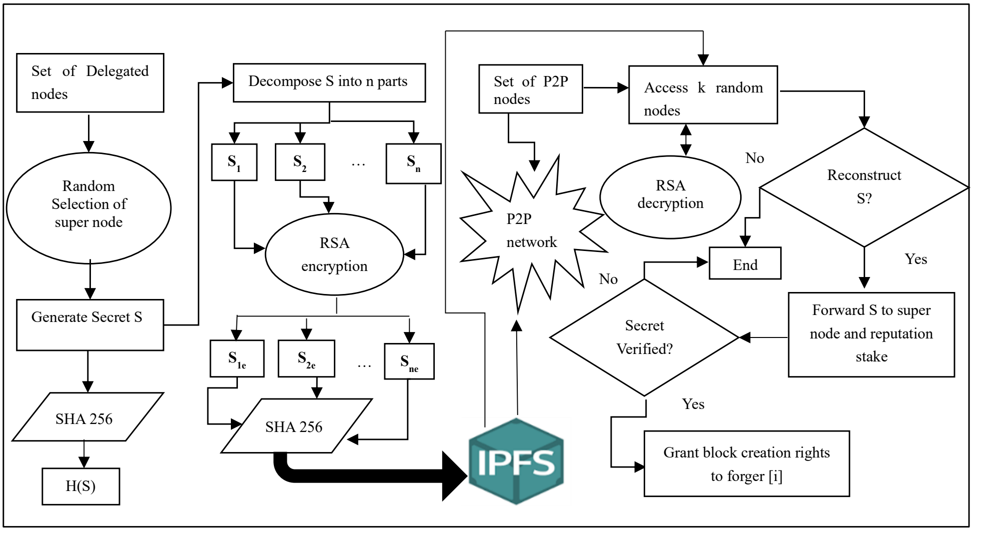

Figure 1. Secret generation and reconstruction

Algorithm 1: Secret generation

Data: F_p is a finite field and p is a prime number, Secret $S \in F_p$, threshold value k, number of secret shares n, large prime numbers p_1,p_2

Result: Secret Shares (S_1,S_2,...S_n), H(S)

$f_0 \leftarrow S$; `/* S is a Secret value */`

$H(S) \leftarrow SHA256(S)$; `/* Apply SHA-256 */`

Choose Random coefficients a_1,a_2,a_3,...$a_{k-1} \in F_p$;

Construct polynomial f(x)=$a_{k-1}x^{k-1} + a_{k-2}x^{k-2} + ... + a_2x^2 + a_1x^1 + S$;

Evaluate the polynomial **for** i= *1 to n* **do**

  Select x_i randomly from F_p s.t. $x_i \neq x_j$ ∀ j ∈ $(1, 2, 3, ...i - 1)$;

  Compute y_i = f(x_i);

  S_i =(x_i,y_i)

end

Algorithm 2 presented the encryption scheme RSA used by our proposed consensus approach to encrypt each S_i to corresponding encrypted value S_{ie}. Algorithm 3 computes hash value of every encrypted share as $CID_i = H(S_{ie})$ and these shares must be stored on at least n distinct nodes using IPFS [16]. In addition, CIDs of secret shareholders nodes are broadcasted to the P2P network with the necessary keys to access these shares.

Algorithm 2: Secret Shares Encryption using RSA algorithm

Data: Set of secret shares M = (S_1,S_2,... S_n) and two large prime numbers p_1,p_2.
Result: Encrypted Shares
Compute Pb_{key_n}=p × q;
Calculate $\phi(Pb_{key_n})$=(p_1-1)×(p_2-1);
Choose an integer e s.t. $1 \leq e \leq \phi$ (Pb_{key_n}) and gcd(e, $\phi(Pb_{key_n})$)=1;
Compute d=e^{-1} ϕ (Pb_{key_n});
Return (ϕ (Pb_{key_n}),e,d);
for *i =1 to n in M* **do**
    S_{ie}=S_i^e(mod(Pb_{key_n})); `/* Get encrypted secret shares */`
end
Return(S_{1e},S_{2e},...,S_{ne}) ; `/* Encrypted Shares */`

Algorithm 3: Distribution of encrypted shares on IPFS

Data: Set of encrypted secret shares
Result: Set of share-holder IPFS nodes ($CID_i = (x_1, x_2)$,CID_2,...CID_n)
for *i =1 to n in M* **do**
    CID_i=SHA256(S_{ie}); `/* Apply SHA-256 */`
end
shares-ipfs= (CID_i=(x_i,y_i)); `/* Store each encrypted share on randomly chosen IPFS nodes */`
for *i= 1 to n* **do**
    CID_i; `/* Broadcast to all IPFS nodes */`
    H(S) ;
    threshold k ;
    $public - key \rightarrow Pb_{key_n} and\ e$
end

Algorithm 4 exhibited the process through functions share_retrieval and secret_-recreate. Here, the miner nodes must get access to more than or equal to k secret shareholders and retrieve S_{ke} encrypted secret shares. Therefore, after getting access to k-encrypted secret shares, decryption needs to be performed by keys supplied through the network. Function secret_recreate is utilized to recreate the secret S'. The miner will compute S' as $H(S')$ and compare it to the transmitted value $H(S)$. If it matches, the miner will send both the secret number S' and the staked reputation coins to the super node. The transmitted secret and reputation value are confirmed by the super node, and if confirmed, that miner is granted block-generating privileges and designated as the forger [16].

Algorithm 4: Secret Share Retrieval and Secret Reconstruction

```
Data: Set of share-holder IPFS nodes (CID_1,CID_2,...CID_n), H(S),
      threshold k, super-node-id
Result: Miner-address, Secret S, reputation-stake-coins
/* Function share_retrieval(miner address)                    */
share − accessed ← 0 ;
S ← 0 ;
for j= 1 to k do
    i ← 1 if node get-access to IPFS node with CID_i then
        share-accessed= map ((CID_i) → key.decrypt( CID_i ));
    else
        i ← i+1 ;
    end
    Return share-accessed (x_i,y_i)
end
/* Function secret_recreate (share-accessed (x_1,y_1))        */
S ← 0 ϵ F_p ;
for  i = 1 to k do
    δ_i = 1 ϵ F_p for j = 1 to k do
        if i ≠ j then
            δ_i = δ_i . −x_j/(x_i−x_j);
        end
    end
    S=S+δ_i.y_i;
end
H'(S) ← SHA256(S) ;
if H'(S)==H(S)) then
    Return 1;
end
```

The process of block creation and verification is shown in Algorithm 5. If the status of the current miner is forger, then calculate the target value as calculated from Equation (1). Hash value with taking as input Secret S, the private key of the forger, previous block hash is then calculated and initial 64 bits are then extracted and termed as "hit value". Target value and "hit value" are compared and if target value $\geq$ hit value then forger can successfully produce the block [16]. The newly created block is then broadcasted to all P2P nodes that can easily verify the hash of the revealed secret value S against the value $H(S)$ supplied by the super node.

The block rewards and penalty system is explained using Algorithm 6. This block is included in the existing chain if a substantial percentage of P2P nodes approve it and reputation coins are awarded to the forger and super node in an 80 : 20 mix respectively as block rewards. If a forger creates a false block, the staked reputation coins are destroyed, and the forger must wait a certain length of time before engaging in the next round of block production [16]. The entire process of block generation is depicted in Figure 2.

Algorithm 5: Block Creation and Verification

```
Data: Set of share-holder IPFS nodes (CID_1,CID_2,...CID_n), H(S), threshold k,
      super-node-id,Miner-address,reputation-stake-coins
Result: Block_header (prev_block_hash, nonce, timestamp), set-of-transaction,
        target-value, hit-value, Secret S
/* Declare retrieved-shares and status                                   */
retrieved-shares = call function share_retrieval(miner-address)
status=call function secret_recreate (retrieved-shares (x_i,y_i ))
if status==1 & miner-address-is-valid==true & reputation-coin(miner-address) ≠
  0 & time-out(miner-address) is inactive)) then
    Grant block-generation-rights (miner-address)
    forger = miner-address
    Calculate target value according to Equation 1
    Label : Compute H = SHA256 (prev_block_hash, pri-key(forger), S,
      timestamp, nonce)
    hit-val = substring (H , 0, 64) ;  /* extract initial 64 bits as hit value
      */
    if hit_value ≤ target-value then
        generate block B
    else
        nonce ← nonce+1 ;
        goto Label
    end
    Return(new-block-created, forger, reputation-coins, super-node-id)
end
```

Algorithm 6: Block Rewards and Penalty

```
Data: new-block-created, reputation-coins, forger, super-node-id
Result: reputation-coins
if new-block-created ==valid ;                     /* if got n confirmations */
 then
    Set reputation-coins(forger) = reputation-coins + 8
    Set reputation-coins (super-node-id) = reputation-coins + 2
else
    Set reputation-coins(forger) = 0
    Set time-out (forger, x) ;       /* put forger in wait state for x time */
end
```

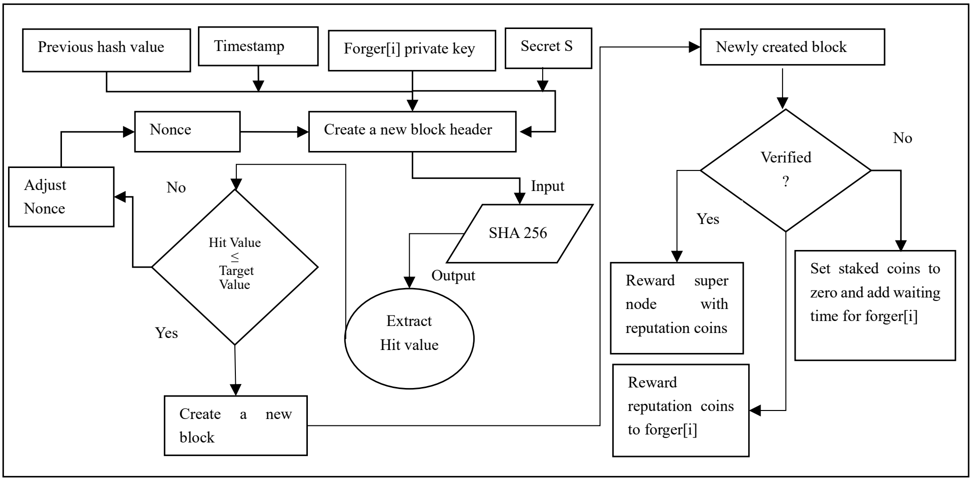

Figure 2. Block generation process

4. Analysis and performance evaluation of DPoAC

Performance evaluation framework

The performance evaluation framework is composed of various parameters that are important in designing consensus protocols. The following aspects are critical in evaluating the performance of these mainstream protocols: applicability, the basis for awarding accounting rights, degree of decentralization, accounting nodes, latency, throughput, fault tolerance rate, energy efficiency, overhead, adversary tolerance, scalability, security, and penalty mechanism. These criteria have been presented thoroughly to demonstrate their importance in consensus protocol design. We have subdivided these performance parameters into three dimensions namely efficiency, structure and security. The efficiency dimension includes all performance-related parameters such as latency, throughput, energy consumption, overhead in terms of computing, network and storage, and scalability. The structural dimension covers applicability, the basis of assigning accounting rights, degree of decentralization, accounting nodes, mining rewards, and IoT suitability [16, 18]. Finally, the security dimension contains the parameters that would ensure the resistance towards several attacks such as 51 percent attack, Sybil attack, and penalty mechanism [16].

4.1. Evaluation of DPoAC against performance parameters

In this section, DPoAC has been evaluated with a comprehensive performance evaluation matrix designed. The performance parameters are divided into three important dimensions namely, efficiency, structural, and security.

4.1.1. Efficiency

We evaluated our prototype using a variety of performance metrics from the efficiency dimension as depicted in Table 2. With a prototype created on a system with an Intel Core i3-3110M CPU, producing a Langrage polynomial with 64 degrees and 256 degrees takes about 15 ms and 46 ms, respectively, as illustrated in Figure 3a. This experiment revealed that even with low-end processors, IoT devices can efficiently produce a Langrage polynomial. The average amount of time needed to upload or download a file on IPFS nodes is shown in Figure 3b. We experimented with file sizes ranging from 1 MB to 1000 MB to see how long it took to load and receive the files.

Table 2
Efficiency comparison of DPoAC against mainstream consensus protocols

Consensus	Latency	Throughput	Energy consumption	Computing overhead	Network overhead	Storage overhead	Scalability
PoW	10 min	$\geq$ 7 TPS (bitcoin) and $\geq$ 15 TPS (Ethereum)	high	high	low	high	not scalable
PoS	1 min	$\geq$ 300 TPS	low	medium	low	high	scalable
DPoS	3 s	$\geq$ 500 TPS	low	medium	N/A	high	partially scalable
PoA	5 min	$\geq$ 14 TPS	medium	high	low	high	partially scalable
DPoAC	42 s (variable)	24–122 TPS	low	low	low	low	scalable

A minimum of 0.98 ms and 1.7 ms are needed to upload and download a file of 1 MB and seems to be quite fast as we have to store the secret shares on an IPFS node with a size much less than that of 1MB. Therefore, the resultant method would be reasonably efficient and fast for secret share distribution and retrieval on IPFS nodes that could vary up to thousands of such nodes. Figure 3c and Figure 3d both represent the computation time used to generate and distribute secret shares as well as their retrieval from IPFS nodes. The computational times grow with the number of shares created and retrieved, as seen in the graphs. In this experiment, we fixed $k = n$, with the highest computation time being recorded as 0.356 s and 0.003 s if $k = 11$ and the lowest computation time as 0.029 s and 0.001 s if $k = 1$ for secret generation and secret share retrieval phases respectively. Hence, the difficulty level of a block being generated could be directly proportional to the number of secret shares being generated. By modifying the block and transaction sizes under optimal conditions, the average latency of our system is measured at 42 s, and TPS in the range of 24 to 122 has been observed. Energy consumption of DPoAC is quite low as compared to other mainstream consensus protocols due to the lack of complex computations. Due to the usage of IPFS and the absence of complex mathematical puzzles, the overhead incurred for storage, network, and computing is greatly reduced. Additionally, the scalability of the proposed system is high as we can easily expand the system to thousands of IoT devices without significantly affecting performance. From these observations, it is implicit that our system is capable to address the limitations of existing consensus protocols in the context of IoT networks.

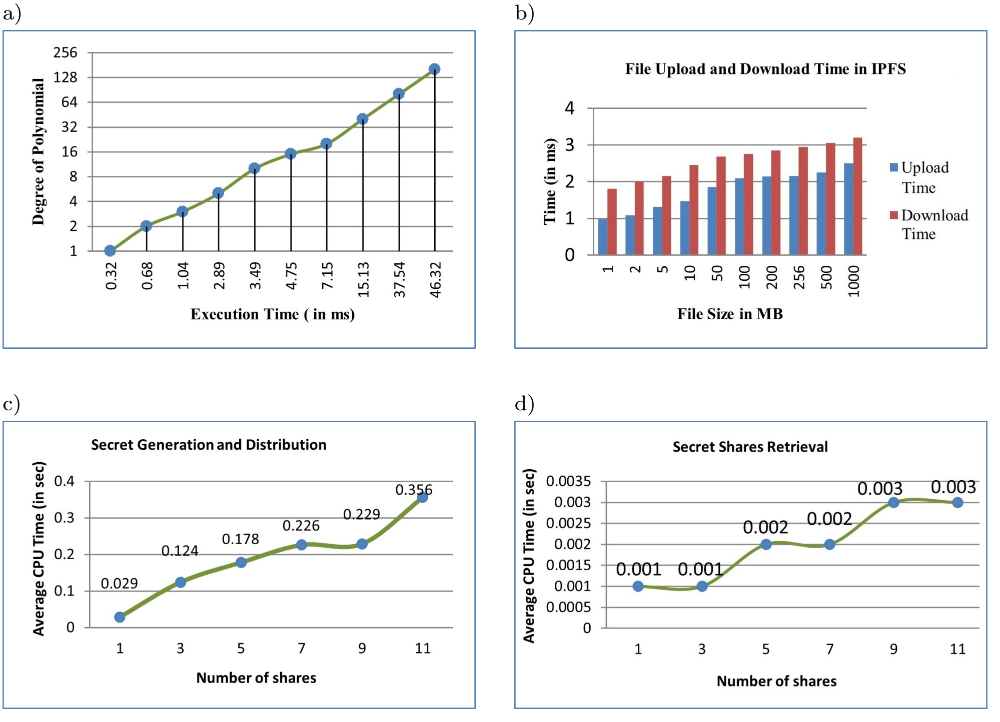

Figure 3. Performance evaluation of DPoAC: a) execution time to build Langrage polynomial; b) average time taken to upload and download a file on IPFS; c) average CPU Time taken for secret generation and distribution; d) average CPU time taken to retrieve the secret shares

4.1.2. Structural

The DPoAC structure is open to the public, and anybody with the required reputation coins can participate in the consensus process. This strategy would be extremely useful in IoT systems due to the usage of a reputation mechanism rather than a financial stake. The degree of decentralization is medium owing to the election of delegated nodes to select a super node to produce a secret and start the block generation process. Access to secret shareholders to expose the secret would provide a foundation for granting block creation rights that would extend from accounting nodes across the entire network [16]. A structural comparison of DPoAC against other consensus protocols is shown in Table 3.

Table 3
Structural comparison of DPoAC against mainstream consensus protocols

Consensus	Basis of assigning accounting rights	Degree of decentralization	Mining rewards	IoT suitability
PoW	Computing Power	high	Monetary rewards for successful miner only	Not applicable due to high resource requirement
PoS	Stake	high	Monetary rewards for successful miner only	Partially applicable due to monetized stake
DPoS	Stake Votes	medium	Monetary rewards for all the delegates distributed equally	Partially applicable due to monetized stake
PoA	Activity Based	low	Monetary rewards for all the stakeholders, and winning miner distributed equally	Not applicable due to monetized stake and high latency
DPoAC	Access to secret Shares	medium	In reputation coins to super node and forger node in 80:20 ratio	Due to the usage of reputation value as a stake and the minimized resource requirements to expose the secret, the method is fully applicable

4.1.3. Security

The proposed consensus mechanism has been demonstrated to be resistant to a number of harmful attacks. Accessibility to more than 50% of these resources, i.e. computing resources in PoW, monetary investment in PoS, and activities in PoA is required for a useful attempt in the consensus process based only on proof of effort [16]. In the intended consensus approach, however, we have merged two methods that will undoubtedly increase the price of destructive efforts while optimizing network security against a 51 percent hazard [16]. Due to the random selection and punishment mechanism for harmful conduct offered in DPoAC [16] the possibility of a DDoS attack on a P2P node or delegated super-node is extremely low and will not breach the protocol. In a Sybil attack, any fraudulent node in the blockchain network might pose as several nodes in order to gain control over the entire network and indulge in undesirable actions. This approach requires the malicious node to pay a stake that would have been forfeited as a result of such activities because it integrates secret sharing and PoS with randomized selection [16]. As a result, the implemented method is capable of preventing such attempts.

Additionally, the use of finite field arithmetic contributes to the security of the SSS scheme because the scattering of the polynomial graph that results from projecting a function on a sufficiently large finite field prohibits an attacker from discovering any aspect of this underlying function. A detailed comparison of DPoAC against security parameters is shown in Table 4.

Table 4
Security comparison of DPoAC against mainstream consensus protocols

Consensus	51 percent attack	Sybil attack	Penalty mechanism
PoW	vulnerable	vulnerable	Does not exist
PoS	less vulnerable	vulnerable	Penalty mechanism would seize the staked coins for the malicious block
DPoS	less vulnerable	vulnerable	The faulty node would be eliminated immediately
PoA	eliminates 51 percent attack	less vulnerable	The faulty node would be eliminated immediately
DPoAC	less vulnerable	less vulnerable	Reputation coins would be lost due to faulty behavior of the forger

5. Conclusions

Through this work, we have implemented and evaluated a lightweight consensus method, DPoAC, that has been derived from classic Proof of Accuracy and PoS consensus protocols. This approach included the SSS scheme to generate and distribute secret values, and IPFS was used to store the individual secret partitions. Although there have been a few papers based on proof-of-accuracy techniques in the past, they were all without concrete implementations. Through this work, we have not only provided detailed algorithms to justify the consensus process but also implemented and evaluated the results. A comprehensive performance matrix has been designed to evaluate and compare the performance of DPoAC. We implemented a prototype, and experimental results show that our protocol works reasonably well in comparison to other mainstream consensus protocols, resolving the issues of energy consumption, heavy resource requirements, and reliance on monetary stakes to become an optimal choice in the IoT context. In future, we would like to test the validity of our protocol at a large scale with real-time IoT data. In addition, we will test the performance of our protocol by including different secret-sharing schemes.

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ENHANCED CLUSTER MERGING AND DEEP LEARNING TECHNIQUES FOR ENTITY NAME IDENTIFICATION FROM BIOMEDICAL CORPUS

Abstract *For mining biomedical information identifying names is the prime task. Complex and uncertain naming styles of biomedical entities are the major setbacks here. Thus, state-of-the-art accuracy of biomedical name identification is reasonably inferior compared to general domain. This study includes Machine Learning and Deep Learning techniques to recognize names from biomedical corpus. In supervised classification, a classifier is built by finding required statistics from training corpus. Accordingly, performance of the system is primarily dependent on quantity and quality of training corpus. But manually preparing a large training dataset with enriched feature samples is laborious and time-taking. Therefore, various techniques were adopted in the literature to make effective use of raw corpora. We have incorporated a novel Cluster Merging technique and Attention Mechanism with BERT embedding for boosting Machine Learning and Deep Learning classifiers respectively. The suggested results outpour that profound techniques are competent and delineate signifying improvement over surviving methods.*

Keywords biomedical named entity recognition, conditional random field, support vector machine, cluster merging, BERT, bidirectional GRU, attention mechanism

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1. Introduction

The task of information extraction (IE) is a critical aspect of natural language processing (NLP) that involves automatically retrieving organized data from unstructured text. Two fundamental tasks involved in information extraction (IE) are named entity recognition (NER) and relation extraction (RE). Further relation extraction between two or more entities necessitate identification of the entity names as prerequisite. A named entity is a succession of words (n-grams) that represents a name of a specific type. Named entity recognition (NER) involves recognizing and categorizing entity names within unstructured text into predetermined classes, which may include person, organization, location, protein, DNA, cell-type, and others. During the past two decades, the evolution of NER systems in multiple languages and fields has been a widely explored research topic. A Significant amount of investigations have been conducted for the development of NER systems in biomedical domain too. However, complex and uncertain naming styles of biomedical entities (such as T-cell, IL-8, mRNA, human immunodeficiency virus (HIV-1) etc.) are the major challenges for identifying biomedical names. These entity names are often long and include hyphen, numeric value, uneven capitalization and uncommon words; these make the classification and boundary identification of biomedical named entities (NEs) rather intricate. And the general NER system outperforms the biomedical NER system in terms of accuracy [69]. Therefore, researchers are still devoting their effort on improving the accuracy of biomedical NER system.

NER approaches can be divided into two primary classes: rule-based approaches, and supervised approaches that rely on Machine Learning or Deep Learning techniques. Rule-based approach uses handcrafted rules for extracting names. This approach yields good results if the rule set has high coverage and can detect complex names that might be difficult with supervised approach. However, rule-based approach is language and domain dependent and not portable. On the other hand, in supervised approach, a classifier is trained. The Machine Learning (ML) algorithm employs annotated samples to train a statistical classifier [22,67]. Thus, the system's effectiveness is majorly dependent on the quality and quantity of the training corpus. Generating a vast quantities of labelled training data with rich feature samples is a challenging and time-taking task. However, there is a huge collection of external raw corpora available that contain valuable information and can be used to augment the annotated training data [37]. To make use of this raw data, effective processing is necessary so that only the relevant parts of the data have a significant influence on the NER results. At this point the significance of word clustering becomes relevant. It is a method of grouping similar words into cluster. This is an efficient method to improve upon the accuracy of labelling and sequencing task like identifying named entity and parts-of-speech tagging etc. Deep learning has appeared as a successful technique, achieving state-of-the-art performance in numerous applications [30], including speech recognition [18], image segmentation [31], image classification [17], and NER [28,35]. Deep learning techniques commonly require a substantial quantity of labelled data for supervised learning, as well as longer training times and greater computing resources compared to traditional machine learning methods. However, despite these requirements, they have demonstrated highly effective results [6].

This paper presents a biomedical Named Entity Recognition (NER) technique that uses several machine learning classifiers and an efficient cluster merging technique to achieve higher accuracy. Support Vector Machine (SVM) and Conditional Random Field (CRF), two widely used ML classifiers are incorporated for GENIA corpus version 3.02 (size 492K words) collected from JNLPBA-2004. The accuracy of a supervised ML algorithm radically relies on the affluence of feature values. With an enhanced combination of candidate features our CRF based baseline NER system gets the highest F-measure of 64.40 with Precision 65.27% and Recall 63.56% and baseline SVM classifier achieves the maximum F-measure of 64.30 along with Precision 62.72% and Recall 65.97%.

Word Clustering has been well anticipated in recent NLP tasks and achieved a greater success; it involves searching for a specific structure or pattern within a dataset that has not been processed or analyzed [41]. So, it is decided to use clustering technique in this Bio-medical NER task. It has been found in the literature that different clustering techniques are available. Farley and Raftery classified clustering into two major categories: partitioning and hierarchical [12]. Han and Kamber suggested additional three types of clustering: model-based, grid-based, and density-based approaches [16]. The explanation of having various clustering techniques is that the perception of "cluster" is not exactly defined [10]. To choose a particular clustering algorithm for any work depends on several parameters like: type of data, size of data and purpose. In this work, both partitioning and hierarchical clustering methods have been used. In partitioning method, a large object is sub divided and grouped into several clusters with every cluster containing at least one element. It is a repetitive process where the objects may be repositioned into other groups based on their relevance. There are two major techniques exist in partitioning clustering method: K-medoids and K-means. The K-means clustering is a straightforward centroid-based technique where overall dataset is divided into 'K' number of clusters, each of which consist similar type of words. On the other side, K-medoids clustering, nearly similar to K-means algorithm; here overall dataset is partitioned into 'K' number of mutually exclusive clusters but clusters are well fitted onto a data point (cluster representative). These representatives are chosen to the closest one (data points) from the cluster's centre rather than the centre point of the clusters (which is used in K-means technique). But as the data points increase the K-means requires maximum time and the K-medoids works convincingly superior to the K-means and also better at scalability for large dataset [36, 54]. So, it is decided to use K-medoids technique from partitioning clustering method. The hierarchical clustering methods organize the overall dataset in a tree like structure. These methods construct clusters by iteratively dividing the data either in a bottom-up or top-down manner. Here brown clustering technique is adopted as a hierarchical clustering. The Brown clustering [3] is a widely used hierarchical clustering method that has found application in various Natural Language Processing (NLP) tasks [32, 39, 45, 55, 58]. It shows better performance for the data which require special care (corpus which includes special symbols and noisy text etc.). Clusters are constructed here based on the statistical analysis of bigram words. However, in the task of named entity recognition (NER), larger contextual words also contain crucial information. To successfully acquire distant information effectively, partitioning clustering technique, specifically K-medoids has been employed. Thus two type of clusters are acquired from two different clustering techniques. Subsequently these are merged to get improve accuracy from the developed biomedical NER system. For using the clustering technique, extra 238K words have been collected from MEDLINE, bio-medical corpora and used in different word representations. After using word clustering, the modified CRF based approach archives the modest F-measure of 77.09 with Precision 75.43% and Recall 78.81% and the modified SVM based system gets the highest F-measure of 75.17 along with Precision 74.41% and Recall 75.94%.

In parallel to machine learning approaches deep learning methods also have been explored for the NER task. A number of deep learning efforts were made by researchers concentrating on NER researches. These methods leveraged neural networks to identify entities by extracting word features from a vector sequence. Deep learning models offer superior performance compared to classical machine learning and rule-based approaches, but still have challenges. Deep learning techniques are classified into two classes: Convolutional Neural Network (CNN) [26] and Recurrent Neural Network (RNN) [8]. CNN is capable of obtaining local features but not context information. Although RNN is able to capture the context information from text because of its sequential nature, recognizing entities becomes challenging due to the prevalence of non-entity words within sentences and the presence of redundant information in a significant portion of the text. To deal with the aforementioned issues, this article introduces a new model named A-BiGRU that tries to identify the names from biomedical corpus. First, the BERT model is applied to generate vectors from words, which can improve the expressiveness of context information. The next phase involves training of the BiGRU network. An attention mechanism is incorporated to overcome the information redundancy. Finally, Softmax function is used to predict the entity label associated with each word, and achieves highest F-measure of 81.20 with Precision 82.89% and Recall 79.57%. In the present study, the suggested model is evaluated on the GENIA corpus version 3.02 and assess its outcomes compared to modern state-of-the-art techniques. The salient contributions of the paper that makes a number of value additions to the literatures are highlighted below.

1. The main aim of this article is to enhance the accuracy of biomedical Named Entity Recognition (NER) task compared to the current state-of-the-art methods. The suggested systems demonstrate superior performance compared to existing approaches.
2. The article presents an innovative approach for merging two distinct classes of clusters, namely hierarchical cluster (Brown cluster) and partitioning cluster (K-medoids cluster), in an efficient manner.

3. The introduced cluster merging technique improves the effectiveness of machine learning classifiers.
4. The BERT model is employed to generate word-level vectors, thereby enhancing the capability of neural networks to extract crucial information.
5. The approach uses an Attention mechanism-based Bidirectional Gated Recurrent Unit (A-BiGRU) to address the issue of information redundancy and enable detailed interpretation of text vectors. This model is directly able to access contextual information from both preceding and succeeding parts of the text.

Outside introduction, this article has been subdivided into 6 other sections. Section 2 discusses relevant previous research. Section 3 explains the baseline NER models. Section 4 presents cluster merging based enhancement of baseline models. Section 5 introduces proposed Deep Learning based NER Model. Analysis and discussion are summarized in Section 6, while Section 7 concludes the paper.

2. Related work

The NER task can be regarded as a problem of labelling sequences. The popular methods used for developing NER systems are rule-based [7], machine learning-based [5], and deep learning-based [21]. The rule based approach relies on handcrafted rules that are created manually and requires a deep understanding of the specific domain; therefore, not easy to pursue for complex NEs [13, 14]. In this section, first, we have mentioned some of the works which used ML classifiers then some deep learning based approaches for identifying the biomedical NEs.

Machine learning classifiers have been extensively used in numerous NER systems to detect named entities in the biomedical field; some of these were Hidden Markov Models [43, 53, 68], Maximum Entropy Classifier [11, 34, 50], Support Vector Machine [22, 40, 47], Conditional Random Field [29, 52, 57] etc.

A machine learning approach leverages labelled training samples to construct a statistical classifier. In the biomedical field there are several publicly available corpora for NER task. Some of the popularly used corpora are GENIA [23], JNLPBA [24], BioCreative [65], and BioInfer [44] etc. In this biomedical NER system development we have used GENIA corpus version 3.02 collected from JNLPBA-2004[1].

In the recent literature, it has been found that there is a growing of interest among the researchers to use raw external corpus to enhance ML based baseline biomedical NER system [41, 55]. Jain et al. proposed a Maximum Entropy based NER system on the Hindi Health domain corpus [20]. Their system incorporated Context Pattern-based extension and other features like POS, synonyms, gazetteers etc. to enhance the performance. Word embedding representation or word clustering is a widely used technique to incorporate external context or global information from unlabeled corpora without direct human intervention.

[1] http://www.geniaproject.org/shared-tasks/bionlp-jnlpba-shared-task-2004

We have adapted K-medoids technique from partitioning clustering and Brown clustering technique as a hierarchical clustering for our NER task. Several relevant studies on these two clustering techniques were made in the previous researches. Toh et al. proposed a system which used noisy user generated text for NER from Twitter corpus by using CRF [56]. Performance of their baseline system was further enhanced by brown clustering and K-means. We came across to a few studies which presented comparative studies between K-means and K-medoids algorithms [1,54]. It has been also observed that several scholars used brown clustering strategies in their researches [2,3,38,42,58–60]. Most of these techniques were intended for processing and extracting information from large unlabelled corpus. Brown clustering was also popularly used for identifying names [32,45,49,58]. It was mainly used in a number of NER systems for post processing tasks or to improve their performances [4,41,46,55].

Deep learning has been widely regarded for sequence labelling problems like NER, POS tagging, sentiment analysis etc. Hammerton et al. [15] suggested a Long Short Term Memory (LSTM) for the NER system on the Reuters Corpus and European Corpus. They designed the LSTM network using SARDNET, a self-organizing map for sequences. Their model achieved the F-measure of 72.88. Huang et al. [19] applied various deep learning methods (LSTM, BiLSTM) along with combination of deep learning and CRF (LSTM-CRF and BiLSTM-CRF) to a number of NLP applications, such as POS tagging, Chunking and NER. They also showed that the efficiency of BiLSTM-CRF was better compared to other models. Katiyar et al. [21] proposed multi-layer BiLSTM to address the problem of nested NER. They executed the model on the ACE2004 and ACE2005 datasets. They obtained F-measure of 69.7 and 70.2 respectively. Yu et al. [66] introduced a method to identify NEs by using multi-layer BiLSTM with a biaffine dependency parsing model. Their system obtained the best F-measure of 80.50 on GENIA dataset.

3. Baseline NER system

The study has explored two popularly applied supervised classifiers, namely Conditional Random Field and Support Vector Machine, in order to build baseline NER model.

Conditional Random Field (CRF)

CRF is a probabilistic classifier that is capable of classifying and organizing sequential data, such as natural language texts [27]. For the NER system development, we have used the CRF++ toolkit[2], an open-source executable framework that is straightforward to use and can be customized. It is capable of handling various NLP tasks, including part-of-speech tagging, named entity recognition (NER), and relation extraction.

[2] https://taku910.github.io/crfpp/

Support Vector Machine (SVM)

SVM, proposed by Vapnik [61], is a widely employed machine learning classifier. Since it is a boolean classifier, a pairwise or one-vs-rest method is applied for multi-class classification. In this NER system development, SVM is utilized as one of the machine learning classifiers. It performs classification by establishing an N-dimensional hyperplane that effectively separates the data into two categories. The NER task consists of two main phases: training and classification, which are executed using YamCha[3]. YamCha is a widely-used, open-source, and modifiable SVM implementation that is broadly applied in numerous NLP applications, including Information Retrieval, NER, Text Mining, etc. Additionally, SVM toolkit, YamCha supports kernel functions. In this experiment the 2nd degree of polynomial kernel has been used.

3.1. Feature set

The literature has demonstrated that use of different features can boost the performance of a supervised NER system. So, it has been experimented with various types of probable features (Word Window, Affix, Parts-of-Speech (POS), Digit, Capitalization, Symbolic, Dictionary, Word Shape etc.) and chosen the best possible feature combinations depending on result.

3.2. Data set

The dataset has been taken from 'Bio-Entity Recognition Task BioNLP/JNLPBA 2004' named GENIA Corpora 3.02 version. The GENIA corpora package consist readymade training and testing data. Dimensions of the training corpus is approximately 492K words and these consist of a total number of named entities 150K. The corpora consist of only 5 NE classes' Protein, Cell-Type, Cell-Line, RNA, and DNA. We have also collected an extra 238K words from MEDLINE bio-medical corpora for using in clustering technique at post processing phase.

3.3. Performance metrics of NER system

We have evaluated the system using F-measure (F) which represents the harmonic mean of precision and recall.

$$F = \frac{\left(1+\beta^2\right)(p \cdot r)}{\beta^2 \cdot (p+r)} \tag{1}$$

Recall is percentage of total NEs which are retrieved accurately whereas precision is percentage of precise observation. β determines the relative weight between recall and precision and typically set to a value of 1.

[3] http://chasen.org/~taku/software/yamcha/

3.4. Result of baseline models

Table 1 presents the accuracies obtained in CRF and SVM based baseline NER models. The maximum F-Measure of 64.40 with 65.27% precision and 63.56% recall are obtained from CRF based model and an F-Measure of 64.30 with 62.72% precision and 65.97% recall from the SVM based model.

From the results of the two baseline models, shown in Table 1, it is apparent that, many of the names are not identified. This may be due to quantity and quality of labelled training corpus. But, manually preparing quantitatively large training data with annotated feature samples is laborious and burdensome. To enhance the performance of these models by intelligently processing the raw external corpus without any human effort, clustering techniques have been incorporated which have been discussed in the next section.

Table 1

The outcomes of the NER models based on CRF and SVM on the GENIA dataset

Combination of different features set	Word Window 7			Word Window 5			Word Window 3		
	P	R	F	P	R	F	P	R	F
CRF: AFFIX-POS-NUM-SYM-CAP-DICT-SHAP	67.75	60.57	63.96	65.27	63.56	64.40	64.27	63.89	64.08
SVM: AFFIX-POS-SHAP-NUM-SYM-CAP-DICT	63.54	64.76	64.02	62.72	65.97	64.30	63.06	64.96	64.00

Precision => P, Recall => R, F-Measure => F

4. Proposed word clustering based enhancement of the NER system

As, the baseline system does not produce satisfactory result, clustering methods have been used to improve the system. Clustering is the most common and popular technique of unsupervised learning. Here, the primary idea is to cluster data points depending on their higher levels of similarity among each other compared to the remaining data points.

It requires no human intervention to group the data samples which means that the grouping is performed on the basis of inherent similarity and difference among the data set. While working with text data set, clustering algorithm is segmenting the text documents into partitions (clusters) where each cluster consists of similar type of words like synonyms, syntactically similar words, different tense form of a particular word, etc. There are several clustering methods available as discussed earlier, here two types of word clustering techniques have been integrated to boost up the performance of the system, one is partitioning method and another is hierarchical method. There are also, several techniques exist depending on partitioning and hierarchical methods, from where K-medoids and Brown clustering have been chosen.

4.1. K-medoids clustering

To perform K-medoid clustering (see Fig. 1), the whole document have been converted into vector points, by assigning weights to each word based on the term frequency-inverse document frequency (tf-idf) calculation and then form matrix by the idea of Vector Space Model (VSM) [51].

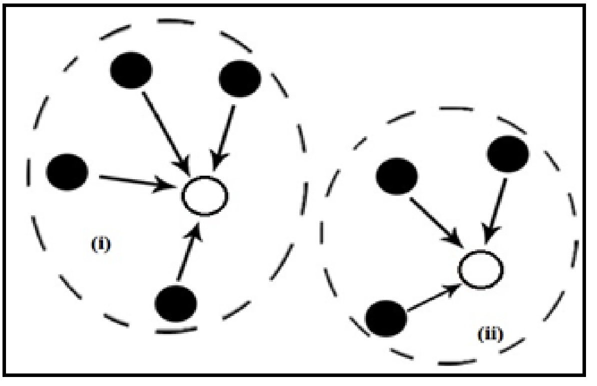

Figure 1. K-medoids cluster

Then k number of random vector points have been chosen as the initial representatives and calculate the distance from all other remaining vector points to find the closest-to-representative for initial mapping (to form a cluster). After that, we have again selected a random non-representative vector point and calculated the total cost. This random selection procedure of non-representative vector points will continue until we get the better value of the total cost from the previous selection and finally, we have swapped the best non-representative point with the initial representative point. As for example, according to Figure 1 there are two clusters where the filled points are non-representative vector points and bare points are representative vector point. The K-medoid approach followed in this study is described below.

Procedure of K-Medoid clustering technique:

1. Randomly pick 'k' samples as preliminary representative points of k clusters, according to the distance of residual samples and the representative point objects, remaining samples are allocated to nearby cluster.
2. Randomly choose a non-representative point.
3. Replace the representative point by non-representative point and check if quality of the cluster is improved. If so, then preserve the substitution; else discard it.

Repeat step 2 to 3 till no change.
The quality of clustering can be assessed using a Silhouette cost function, which calculates the average variation between objects and their representative points.

4.2. Brown clustering

The Brown clustering has been adopted as hierarchical clustering technique. This clustering technique is based on bigram statistics of sequential data such as input text and the output of this technique is a binary tree. The Figure 2 depicts an example of a binary tree as a result of the hierarchical clustering. This binary tree contains 7 words at the leaf nodes from GENIA corpus. Every word is depicted by a binary string within the rectangle, which is generated from the sub-paths string originating from the root of the tree. The size of the word representation is equal to the height of the tree. Now to calculate the number of clusters from this tree, it is necessary to perform tree pruning at a specific level. For example, if pruning is performed at level 2, then we get 4 clusters, which are [CD28, NF-Kappa], [a, the], [HIV-1] and [of, for]. Now the noticeable fact is that, among these four clusters, each cluster's words have the same prefix of bit string with the length of 2 (at the cutting level). These prefixes represent each unique cluster, so we have used these prefixes of the bit strings as training feature. For the experimental purpose, we have used prefix length of 4, 8 and 12.

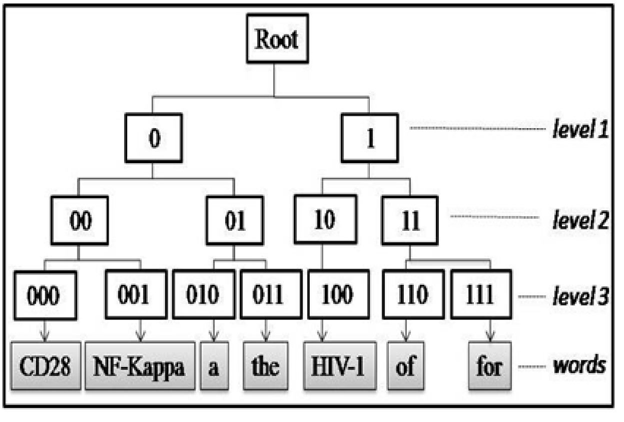

Figure 2. Brown cluster

4.3. Cluster merging

Now, two different sets of clusters have been obtained by pruning Brown cluster and K-Medoids Clustering. Next, these two techniques are combined to attain higher efficiency from the NER system. The proposed cluster merging technique is based on the perspective of similarity of tokens in the candidate clusters. The cluster merging algorithm decides whether to merge those two clusters into one unique cluster; if the test clusters are of higher similarity then merge them into one single cluster; as a result, we get a new one. The proposed cluster merging technique is described in Algorithm 1.

Algorithm 1 Cluster Merging Procedure

Require:
1. Set of K-Medoids Clusters: $KM = \{km_1, km_2, \cdots\cdots\}$
2. Set of Brown Clusters: $B = \{b_1, b_2, \cdots\cdots\}$

Ensure:
1. Merged Clusters: $MC = \{mc_1, mc_2, \cdots\cdots\}$

```
Begin:

for each b_i from B do
    T=0;                                          ▷ Set Initial Threshold
    for each km_i from KM do
        C = (b_i ∩ km_j);                         ▷ Common Words in Current 2 Clusters
        A=(No. of Words in km_j + No. of Words in b_i)/2;
        /*Average No. of Words in Current 2 Clusters */
        P = (C/A * 100)%;                         ▷ Calculated New Threshold
        if (P > T) then
            T=P;
            Temp=j;                               ▷ Store Index or ID of K-Medoids cluster
        end if
    end for
    mc_i = MERGE(b_i, km_Temp);                   ▷ Merge these two clusters
end for
```

For each brown cluster b_i, it checks each and every K-medoids cluster km_j to find the highest similarity. This highest similarity is judged by the similarity threshold value (T) which is initially taken as zero. First, we have extracted the common or similar words (C) from the two current clusters (b_i, km_j). Since all clusters are not of same size, so we have taken the average (A) of the two adjacent clusters and calculate the percentage of similarity (P). For each iteration, the threshold value T will be updated, if the value of P is higher; subsequently mark the location of km_j (j) into 'Temp' for further merging operation. Finally, the two adjacent clusters (b_i, km_{Temp}) are merged into a new cluster mc_i. This process is repeated for each and every brown cluster b_i to obtained the corresponding merged clusters. This merged cluster set is employed as a feature in the experiment.

By integrating word clustering technique CRF based approach attains an F-Measure of 77.09 with 75.43% precision and 78.81% recall and SVM based approach accomplishes an F-Measure of 75.17 with 74.41% precision and 75.94% recall. Two comparative studies of the CRF and SVM based baselines have been shown with their clustering based enhancements in Figure 3 and Figure 4. These two figures justify the importance of incorporating cluster margin technique as a post processing technique.

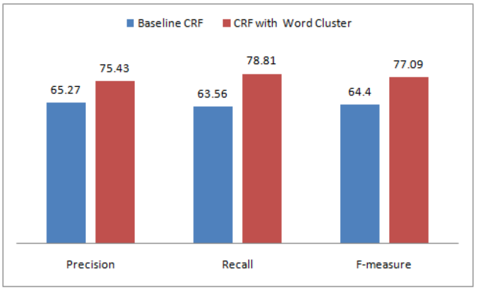

Figure 3. Comparative result of CRF based baseline model with its clustering based enhancement

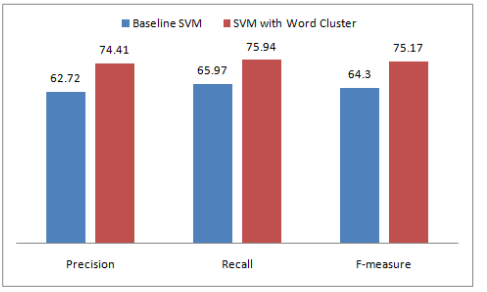

Figure 4. Comparative result of SVM based baseline model with its clustering based enhancement

5. Proposed deep learning based NER model

This section outlines the architecture of the proposed deep learning model (A-BiGRU), as depicted in Figure 5.

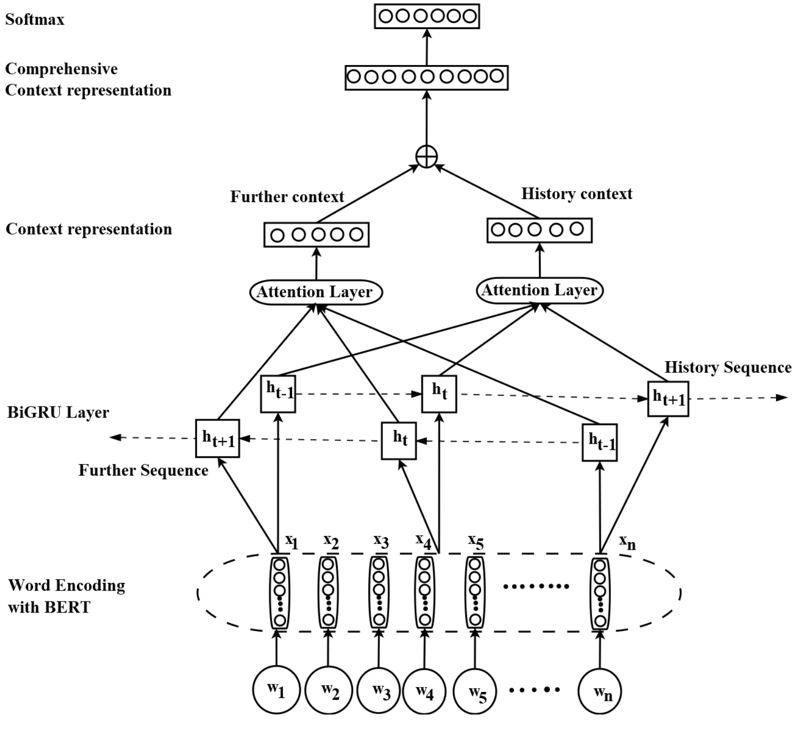

Figure 5. The architecture of the A-BiGRU

The A-BiGRU model includes three essence layers: the input feature layer, BiGRU layer, and attention layer, which are used for entity recognition. The BERT model is used in the input feature layer for representing the word into vector form. The BiGRU network mainly collects texts' context information. The attention mechanism allows the model to gain a greater comprehension of the text's detailed features, while the Softmax classifier is employed to predict the entity label associated with every word.

5.1. Embedding layer

The BERT approach employs bidirectional transformers as encoders which combine the contextual knowledge from both sides of the present word. During the process of learning word vector representations, the encoder is no longer follows a sequential approach to identify words within sentences. Instead, it masks or replaces some words at random in specific proportion of the context and generates predictions for the original words. Moreover, in the BERT model, there are training tasks that operate at the sentence level, focusing on comprehending the contextual relationship that exists within sentences. The specific technique is employed to randomly substitute certain sentences, and the encoder leverages the preceding sentence to determine whether the subsequent sentence is the original one. These two tasks cooperatively obtain vector expressions at word level and sentence level.

The BERT includes a mechanism for fine-tuning parameters. The input sentence sequence is denoted as $w = ([CLS], w_1, w_2, ..., w_n, [SEP])$, in this given context, $[CLS]$ represents the beginning of a sample sentence sequence, while $[SEP]$ is used to indicate the space that separates the sentences. They are used for training at the sentence level. Each word vector is represented by three components: a word embedding vector, a sentence embedding vector, and a position embedding vector. The word embedding is demonstrated as

$$e^w = \left(e^w_{[CLS]}, e^w_{w_1}, e^w_{w_2}, ..., e^w_{w_n}, e^w_{[SEP]}\right)$$

the sentence embedding (segment embedding) is demonstrated as

$$e^s = (e^s_A, e^s_A, e^s_A, ..., e^s_A, e^s_A)$$

and the word position embedding is demonstrated as

$$e^p = \left(e^p_0, e^p_1, e^p_2, ..., e^p_n, e^p_{n+1}\right)$$

To obtain the word feature input for the BERT model, we merge these three embedding vectors together, as shown in Figure 6.

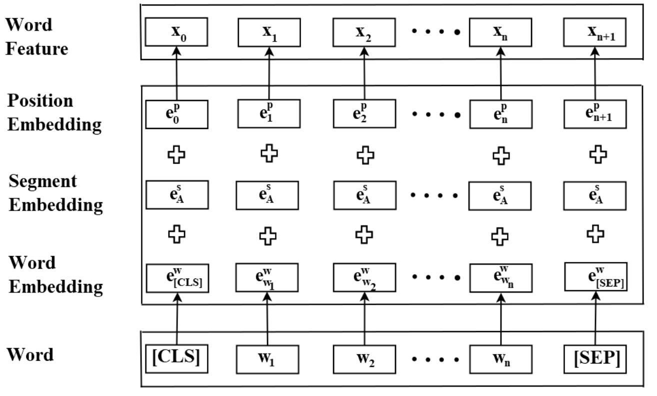

Figure 6. The architectural design of the A-BiGRU

The final representation of the word vector obtained after training is performed by the Formula (2) and serves input for the BiGRU and self-attention layers.

$$x = [x_1, x_2, x_3, ..., x_n] \tag{2}$$

5.2. BiGRU and Attention Mechanism (AM)

Basically, entity recognition involves the task of sequence labeling. In this case, BiGRU is utilized for sequence modeling, which enables the extraction of contextual knowledge from a series of word vectors. BiGRU consists of two GRUs, namely forward and backward. Each GRU includes an update and a reset gate. In order to address the issue of gradient disappearance or explosion in RNNs, the gate structure is employed to selectively retain context information. The GRU architectural design is demonstrated in Figure 7.

The GRU computations are shown as follows:

$$r_t = \sigma\left(w_r \cdot [h_{t-1}, x_t] + b_r\right) \tag{3}$$

$$z_t = \sigma\left(w_z \cdot [h_{t-1}, x_t] + b_z\right) \tag{4}$$

$$\widetilde{h_t} = tanh\left(w_h \cdot [r_t \cdot h_{t-1}, x_t] + b_h\right) \tag{5}$$

$$h_t = (1 - z_t) \cdot h_{t-1} + z_t \cdot \widetilde{h_t} \tag{6}$$

Where the sigmoid function is denoted by σ and $\cdot$ symbolizes dot product. The symbol w represents weighted matrices and b symbolizes bias. The input vector is x_t, the hidden state is h_t at time t. The update gate is z_t which regulates the impact of the preceding output on the present state. The reset gate is r_t which is applied to regulate the significance of h_{t-1} to $\widetilde{h_t}$. $\widetilde{h_t}$ indicates the information in the current unit that has to be updated. The length of a sequence is captured by both gates. In contrast to LSTM, GRU offers a simpler structure and faster training speed.

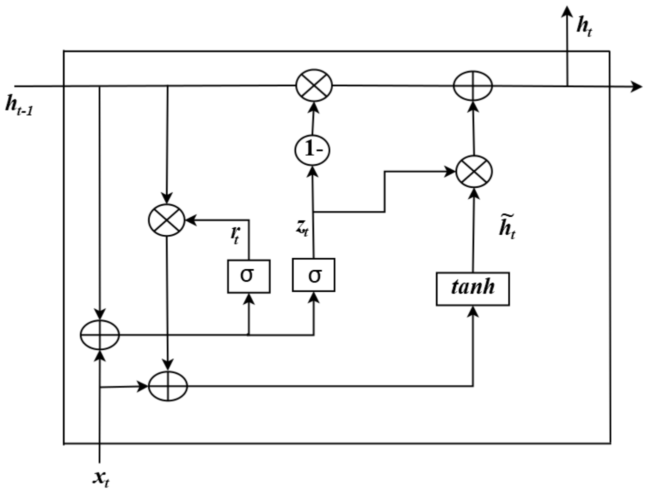

Figure 7. The architectural design of the A-BiGRU

The BiGRU employed in this article consists of both forward and backward GRU. The forward layer of GRU is denoted by $\overrightarrow{h_t}$ and the backward layer of GRU is denoted by $\overleftarrow{h_t}$. BiGRU is used to fetch the future contextual features $\overrightarrow{h_t}$ and the historical contextual features $\overleftarrow{h_t}$ from the context, using formula (7) and formula (8). The output of BiGRU layer is obtained by merging the outputs of forward and backward layer at time t, as illustrate in formula (9).

$$\overrightarrow{h_t} = GRU\left(x_t, \overrightarrow{h_{t-1}}\right) \tag{7}$$

$$\overleftarrow{h_t} = GRU\left(x_t, \overleftarrow{h_{t-1}}\right) \tag{8}$$

$$h_t = \left[\overrightarrow{h_t}, \overleftarrow{h_t}\right] \tag{9}$$

The objective of BiGRU is to preserve the contextual properties of the sentence sequence. However, the significance of semantic relationship of every word has a different importance in the sentence sequence for the NER task. Normally the text (dataset) contains a huge amount of unnecessary words (not name words), resulting in redundant information. It is challenging for the BiGRU model to fetch crucial information from sentence sequences. Consequently, attention mechanism is incorporated in the BiGRU model to capture further significant information. It can give more weightage to important information and understand the meaning of sequences better. In the A-BiGRU model (BiGRU with attention layer), two attention layers are employed to handle the preceding and subsequent contextual information separately. These pieces of information are then concatenated in the AM (Attention Mechanism) module and fed into the Softmax classifier. The architecture of the A-BiGRU model is shown in Figure 5.

A-BiGRU employs the dropout layer and the Softmax classification layer to obtain the probability distribution required for classification. Dropout layer is employed to mitigate overfitting. The cross-entropy loss function is applied here, which is preferable over the mean square error approach. Adam optimizer is widely recognized as an efficient and successful method for fine-tuning model parameters through backpropagation [25]. By employing the cross-entropy loss function in the stochastic gradient descent technique, the likelihood of gradient disappearance is minimized. The loss function is represented in formula (10) as follows.

$$L_{total} = -\frac{1}{num} \sum_{Sp} [ylno + (1-y)\, ln\, (1-o)] \tag{10}$$

Where, 'num' represents the number of words in the training data, 'Sp' denotes batch sample size used for training, 'y' corresponds to predicted sample label, and 'o' represents actual sample label.

The complete technique for learning (A-BiGRU) is presented in Algorithm 2.

Algorithm 2 A-BiGRU

Require:
1. $w = w_1, w_2, \cdots\cdot, w_n$; ▷ w represents sequence of words.
2. $o = o_1, o_2, \cdots\cdot, o_n$; ▷ o is the actual sample label.

Ensure:
1. $y = y_1, y_2, \cdots\cdot, y_n$; ▷ y represents predicted named label.

Begin:

Step1: The BERT model is used to generate word vector as $x = [x_1, x_2, x_3, \cdots\cdot, x_n]$;

Step2: By using BiGRU, the current and preceding contextual features, denoted as $\overrightarrow{h_t}$ and $\overleftarrow{h_t}$, are extracted from the feature vectors, using formula 7 and formula 8;

Step3: The current and past context representations are combined to obtain comprehensive context representations denoted as $h_t = [\overrightarrow{h_t}, \overleftarrow{h_t}]$, using formula 9;

Step4: The h_t is inputted into the Softmax function to obtain the appropriate class designations, denoted as (y).

Step5: The cross entropy function is employed to optimize the parameters of model and sequence of entity labels, using formula 10;

Step6: return $y = y_1, y_2, \cdots\cdot, y_n$;

5.3. Parameter setting

The model parameter settings include an embedding size of 768 and a hidden state dimension of 100 for the GRU. The rate of learning is set to 0.001, while the rate of dropout is 0.5. The batch size used during training is 32. The proposed model has a total of 121 million trainable parameters. Back Propagation and Adam's Optimizer are used to train the network. Table 2 displays parameter configuration of the suggested model.

Table 2
Parameter selection

Parameter	Values
Embedding Size	768
GRU unit dimension	100
Learning	0.001
Optimizer	Adam's Stochastic Optimizer
Dropout	0.5
Batch size	32
Activation function	Softmax
Number of trainable Parameters	~121M

6. Discussion and analysis

Noticeable improvements have been observed in both CRF and SVM based models, after incorporating clustering technique, but the deep learning based BIGRU with Attention Mechanism outperforms all of them by achieving highest F-Measure of 81.20 with 82.89% Precision and 79.57% Recall. Figure 8 demonstrates a comparative analysis of the baseline outcomes and the improvements achieved by incorporating word clustering in the different stages of developing the NER systems along with A-BiGRU model.

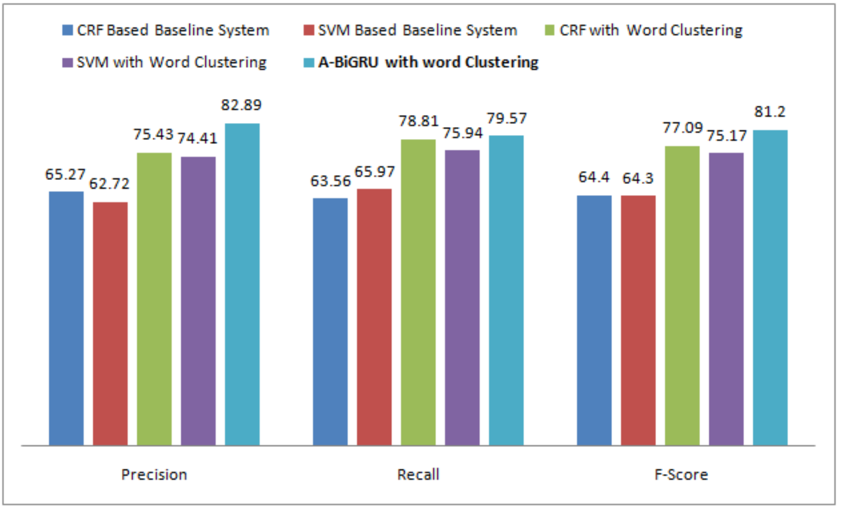

Figure 8. Comparative study of baseline models with their clustering based enhancements and A-BiGRU

A number of researchers worked on biomedical corpus to develop NER systems for identifying NEs like: Protein, Cell-Type, Cell-Line, RNA, DNA etc. Although none of these systems achieved ample accuracy like general domain NER systems. We have listed several advanced systems that utilized the GENIA dataset, demonstrating their state-of-the-art performances, and presented a comparison of the proposed systems with them in Table 3.

Zhou and Su introduced the top-performing model in the JNLPBA 2004 shared task [68], which attained an impressive F-measure of 72.55. Their system utilized a combination of deep knowledge about domain and various features to achieve such results. Tang et al. developed machine learning-based BNER systems with 3 distinct word representation (WR) features; including word embeddings, clustering and distributional representation [55].

Table 3

Comparison with existing approaches

NER System	Precision	Recall	F1-Score
[55]	70.78	72.00	71.39
[68]	75.99	69.42	72.55
Proposed SVM with Word Clustering	**74.41**	**75.94**	**75.17**
[9]	74.17	77.87	75.97
[48]	74.17	77.87	75.97
Proposed CRF with Word Clustering	**75.43**	**78.81**	**77.09**
[21]	76.7	71.1	73.8
[33]	76.2	73.6	74.9
[63]	79.0	77.3	78.2
[64]	78.6	79.3	78.9
[62]	77.9	80.7	79.3
[66]	81.80	79.30	80.50
Proposed A-BiGRU	**82.89**	**79.57**	**81.20**

This system reached an F-Measure of 71.39. Ekbal, Saha and Sikdar used genetic algorithm and proposed a SOO based ensemble system on GENIA dataset which attained an F-measure of 75.97; it currently produces the superior result [9, 48] for any machine learning based NER. The proposed system (CRF with cluster merging technique) outperforms the existing machine learning techniques by accomplishing the highest F-measure of 77.09.

Katiyar et al. introduced an innovative method based on recurrent neural networks to address both nested named entity recognition and nested entity mention detection. Their approach achieved the highest F-measure (F1-Score) of 73.80 on the GENIA dataset [21]. Lin et al. proposed an Anchor-Region Networks (ARNs), a sequence-to-nuggets architecture for nested entity mention detection. Their technique produced the greatest F-measure of 74.90 on the GENIA dataset [33]. Xia et al. suggested a Multi-Grained Named Entity Recognition (MGNER) technique to detect and recognize entities on multiple granularities. Their approach achieved an F-measure of 78.20 [63]. Yan et al. proposed pre-trained Seq2Seq model BART to performed Named Entity Recognition (NER) task. They achieved F-measure of 78.90 on the GENIA dataset [64]. Wan et al. suggested span-based graph method for identifying the nested named entity. They obtained F-measure of 79.30 on this dataset [62]. Yu et al. introduced a deep learning method by incorporating multi-layer BiLSTM with Biaffine dependency parsing model. Their system obtained the best F-measure of 80.50 on GENIA dataset [66]. The proposed deep learning model A-BiGRU surpasses it by accomplishing the highest F-measure of 81.20.

Figure 9, and Figure 10 present comparative analysis of A-BiGRU with Multilayer BiLSTM [66] on the validation dataset regarding accuracy and loss function respectively.

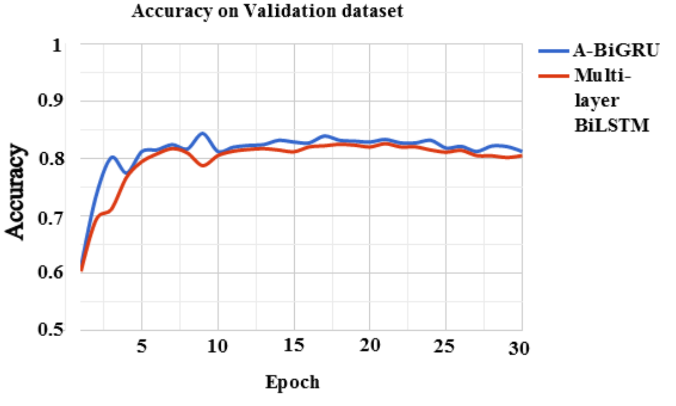

Figure 9. A comparison between A-BiLSTM and Multi-layer BiLSTM [66] models based on the accuracy observed on the validation dataset

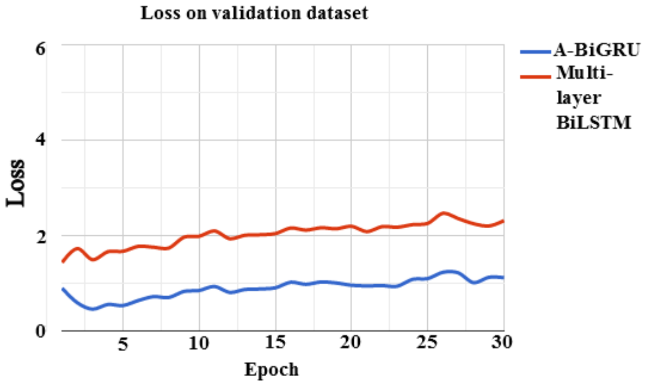

Figure 10. A comparison between A-BiLSTM and Multi-layer BiLSTM [66] models based on the loss observed on the validation dataset

7. Conclusion

This study has demonstrated the construction of a biomedical NER system using a comprehensive set of features incorporating two widely used machine learning classifiers, CRF and SVM. Quality and quantity of tagged training data with enriched set of feature samples are prerequisite criteria for a better performing supervised system. But while sufficiently large such natural language corpus is not available; intelligent processing of raw external corpus can play an imperative role to obtain required statistics to improve the classifier. The clustering technique is one of such widely adopted promising approach. In this biomedical NER system development two type of word clustering techniques, partitioning and hierarchical have been incorporated, where K-medoids and Brown clustering have been chosen respectively. A combination of these two clustering methods has achieved much improve performance over the baseline SVM and CRF based models. In parallel to these we have also prepared a deep learning based NER system (A-BiGRU) which combines BERT language model, BiGRU with Attention Mechanism. The proposed model intelligently captures the context information by incorporating the BERT model to improve the expressiveness of context information by generating word vectors and the Attention Layer is incorporated to overcome the information redundancy. While comparing the proposed system with the state-of-the-art methods, it is found that the result of the proposed system sidelines the surviving NER systems in this domain.

One of the tricky issues in the task is dealing with ambiguities, in which the same term might represent multiple entities (such as a word "Cell" can refer to a biological cell or can refer to an experimental or laboratory setting. Again, another word "Protein" can refer to specific type of body substances or dietary components.) in different situations. As a result, the accuracies of these systems are diminished and certain entities may be overlooked. In future we would like to resolve these issues and extracting the relation among these entities.

Author contributions

The manuscript has been written, edited, and evaluated by all authors.

Conflict of interest

The authors affirm that they have no financial or commercial affiliations that could potentially create a conflict of interest in relation to the research.

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THE POWER OF INTELLIGENCE EMERGING FROM SWARMS

Abstract *Swarm intelligence (SI) is a field of study that seeks to understand and model collective behaviors observed in natural social systems, such as ant colonies, bee hives, termite mounds, flocks of birds or schools of fish. The central principle of SI is that complex intelligent behaviors can emerge from the interactions of large numbers of simple individual entities, without any centralized control or monitoring. SI researchers aim to uncover the underlying principles and mechanisms behind this SI, with the aim of applying these concepts to solve complex problems in areas such as optimization, robotics, transport, IT, etc. As the field continues to evolve, SI is expected to have an increasingly significant impact on our understanding of biological systems and our ability to design intelligent systems capable of adapting and thriving in complex environments and dynamic. This article aims to introduce the reader to the field of SI, presenting its fundamental concepts, key principles, existing applications, and prospective future developments.*

Keywords swarm intelligence, collective behavior, optimization

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1. Introduction

Nowadays, there is increasing interest in solving optimization problems without relying on prior knowledge. Indeed, prior knowledge about the problem, such as the mathematical model, constraints, and objective function, is often necessary to design effective optimization algorithms. However, many real-world problems often possess complex characteristics, such as nonlinearity, discontinuity, multimodality, and non-differentiability, which make it difficult to formulate an accurate mathematical model or acquire prior knowledge by traditional mathematical techniques [20]. Therefore, researchers are now exploring approaches to solve optimization problems based on limited or no prior knowledge. This means developing algorithms that can adapt and learn from the problem itself, rather than relying heavily on explicit knowledge provided by experts or domain-specific information. For this, swarm-based algorithms have emerged as promising approaches to solve optimization problems in various fields [26]. Their ability to explore complex search spaces and find optimal or near-optimal solutions, even in the absence of prior knowledge, makes them valuable tools for tackling real-world challenges.

Swarm intelligence (SI) is a phenomenon in which simple agents, such as ants, bees and birds, work together to accomplish complex tasks that would be arduous or inaccessible for a single individual. This collective behavior involves decentralized decision-making, self-organization, adaptive responses to environmental dynamics, and the emergence of new properties that exceed the capabilities of individual agents. SI algorithms capture these principles and apply them to address different challenges in optimization, control, classification, clustering, routing, and prediction in various fields including engineering, robotics, biology, economics, social sciences and humanities [34]. These algorithms allow efficient exploration of large search spaces, convergence towards optimal or near-optimal solutions and the simultaneous management of several objectives or constraints. Additionally, they demonstrate scalability, robustness, fault tolerance and adaptability to dynamic or uncertain environments, thanks to their decentralized and distributed nature [9]. However, SI algorithms face challenges such as premature convergence, scalability issues, parameter sensitivity, and the need for rigorous theoretical foundations.

The main contribution of this paper is to provide future researchers and scholars with a roadmap to better understand current swarm-based systems and identify opportunities for further progress and improvement by exploring the underlying mechanisms of intelligence collective in natural swarms.

The paper is structured into four main sections: Section 2 explains the concept of SI, including its principles, design approaches and key characteristics. Section 3 presents an overview of SI algorithms. It covers their designs, uses and applications in other fields. The section also discusses the limitations of current SI approaches and highlights some of the challenges and potential directions for future research. Finally, Section 4 concludes the paper.

2. Swarm intelligence

Swarm Intelligence (SI) is a concept that originated in the field of cellular robotic systems, but has since expanded to various other areas, including optimization, sensor networks, data mining, machine learning, image processing, computer vision, etc. It is considered a branch of collective intelligence (Fig. 1), which falls under the broader framework of computational intelligence, which itself is a subset of artificial intelligence (AI) [41].

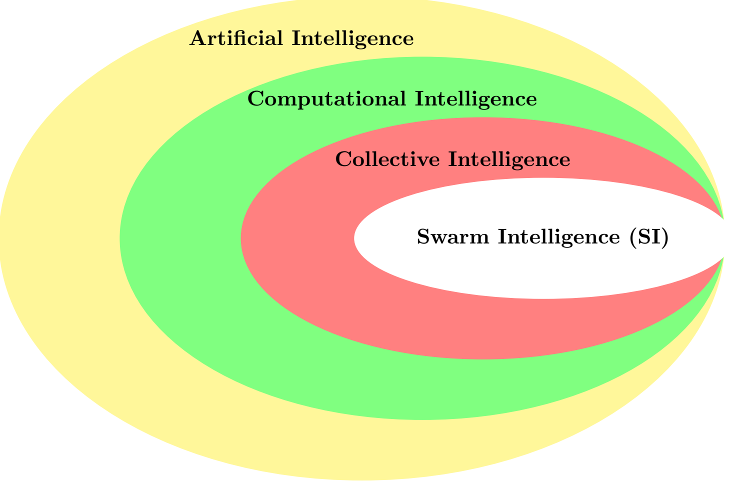

Figure 1. Where does "Swarm Intelligence (SI)" belong in the areas of Artificial Intelligence (AI)?

SI refers to the collective behavior exhibited by a group of relatively simple agents, often called "particles" or "individuals", which are usually autonomous and have capabilities limited cognitive. They may have simple rules or behaviors that govern their actions, but they do not possess a global understanding or awareness of the system as a whole, but local interactions and communication between them generate collective intelligence.

2.1. Principles

When talking about SI, five fundamental principles are often considered guidelines for designing and understanding swarm behavior [32]. These principles are proximity, quality, diversity of responses, stability and adaptability (Fig. 2).

Proximity refers to the concept that agents in a swarm should have the ability to perceive and interact with their nearby neighbors. Local interactions allow them to share information, influence each other's behavior and coordinate their actions. Proximity is crucial for effective communication and coordination within the swarm.

Quality refers to the performance or ability of individual agents based on specific criteria or objectives. Quality is measured based on the specific problem or task at hand. This may involve criteria such as efficiency, accuracy, timeliness, resource utilization or any other relevant indicator. Agents in a swarm must have mechanisms to measure their own performance, based on their local information and perception of the environment, and make decisions accordingly. Agents can contribute to the overall performance of the swarm by considering the quality of their own actions.

Diversity of responses refers to the variety of behaviors or strategies among agents in a swarm. If all agents follow the same behavior or strategy, the swarm may become vulnerable to obstacles or suboptimal solutions. By fostering diversity, the swarm can explore different possibilities and increase the chances of finding better solutions or adapting to changing environments.

Stability refers to the ability of a swarm to maintain its cohesion and functionality over time. This implies that the swarm must be resilient to disturbance, noise or disruption. A stable swarm can withstand external or internal variations and continue to exhibit consistent and efficient behavior. Stability ensures the robustness and reliability of the swarm.

Adaptability refers to the ability of a swarm to adapt and respond to changes in the environment or task requirements. An adaptive swarm can change its behavior, strategies, or structure to adapt to changing circumstances. Adaptability allows the swarm to handle dynamic and unpredictable situations and improves its overall performance and resilience.

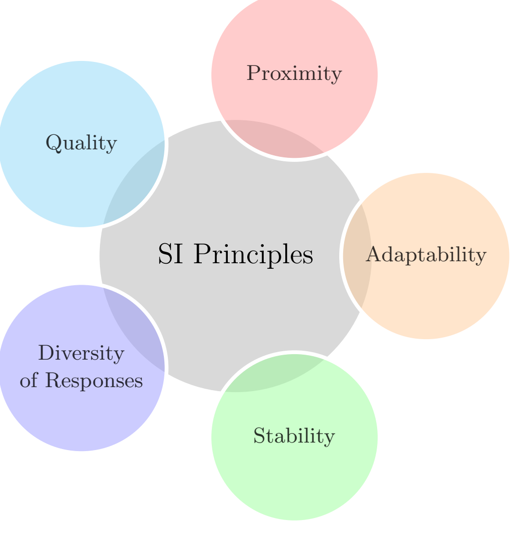

Figure 2. What properties must be present for a system to be considered a swarm-based system?

2.2. Design and features

The design and features of swarm systems encompass a range of aspects that define the fundamental characteristics and behavior of systems composed of multiple agents, called swarms. These aspects can be classified into those concerning individual agents and those concerning the entire swarm. Regarding individual agents, aspects include simplicity, limited memory, sensing capabilities, limited computing resources, and limited communication capabilities. As for the whole swarm, the aspects involve emergent behavior, scalability, decentralization, adaptability, communication protocols, fault tolerance, task allocation mechanisms, cooperation and collaboration, as well as robustness in the face of agent heterogeneity.

2.2.1. Agent aspects

Agent aspects in swarm systems refer to the unique features that distinguish individuals within the swarm.

First, the simplicity of the individual agent. The principle of swarm systems emphasizes that individual agents should be kept simple compared to a single sophisticated system serving the same goal. Agent simplicity helps reduce the complexity of each agent's behavior and control, making the swarm easier to manage and scale [18].

Second, limited memory. Basic agents in swarm systems are assumed to have limited memory. This means that the size of memory available to each agent remains constant regardless of the size of the problem or the number of agents in the system. Limited memory is a deliberate constraint placed on agents to simplify their design and control while promoting scalability and efficiency [10].

Third, sensing capabilities. The sensing capabilities of agents in swarm systems determine their perception of the environment and influence their decision-making process. These capabilities are often designed to be limited, consistent with the principle of simplicity of swarm systems. Agents generally have a local perception of the environment and base their decisions on the information available within their detection radius. This limitation allows for scalability and efficient coordination within the swarm, as agents only need to process and take into account local information rather than the entire global state of the environment [39].

Fourth, limited computing resources. The computing resources available to the agents are designed to be sufficient to execute the required algorithms and take into account their limited memory capacity [8].

Fifth, limited communication. Communication between agents in a swarm system is generally limited. A distinction is made between implicit and explicit communication, with implicit communication occurring as a side effect of other actions or via the environment. Explicit communication is a deliberate act aimed at conveying information to other agents. Explicit communication can take various forms, such as short-range point-to-point communication, global broadcasting, or the use of distributed shared memory [25].

2.2.2. Swarm aspects

Swarm aspects in swarm systems encompass properties related to the collective behavior and functionality of the entire swarm. First, collective intelligence. Swarm systems leverage the intelligence, knowledge, skills, and perspectives of all individuals in the swarm to solve complex tasks and make robust decisions that would be difficult for a single individual [15]. Second, scalability. Swarm systems provide the dynamism and flexibility to increase or decrease the number of individuals depending on the task at hand. This allows for efficient resource allocation and adaptability to different environments and mission requirements [40]. Third, redundancy and robustness. The existence of multiple individuals in swarm systems introduces positive redundancy, which improves reliability and robustness. Even if an individual fails or encounters malfunctions, the swarm can continue to function and accomplish its mission. This ensures the success of any mission, especially in harsh and dangerous environments [40]. Fourth, decentralization. Swarm systems operate on a decentralized principle, in which individuals interact locally with their neighbors without any centralized control or explicit communication. This decentralized approach reduces communication costs and improves system resilience. It also allows for rapid response to changes in the environment without the need for a hierarchical chain of command [15]. Fifth, emergent behaviors. Swarm systems can exhibit emergent behavior, where complex global behaviors emerge from simple local interactions between individuals. This emergent behavior allows the swarm to accomplish tasks such as exploration, foraging, or gathering without the need for explicit coordination. It contributes to the self-organizing and adaptive characteristics observed in natural swarms, leading to efficient and autonomous functioning [16]. Sixth, parallelism and task decomposition. Swarm systems benefit from parallelism. This is done by breaking down the overall task into subtasks. Each individual in a swarm performs one simultaneously, which helps speed up task execution. This approach allows for effective management of large-scale and time-sensitive tasks, especially tasks that would be impractical or impossible to accomplish alone [8]. Seventh, heterogeneity. Swarm systems can incorporate heterogeneous individuals with different physical properties and capabilities. These different individuals can complement each other, leveraging their unique abilities to optimize performance and achieve various goals [38].

3. SI algorithms

3.1. Overview

SI algorithms were designed taking inspiration from collective behaviors observed in diverse biological groups and swarms, ranging from simple organisms to complex social animals. Some examples include bees in composing and constructing hives, termites creating complex tunnel systems, ants finding paths when searching for food, birds flying in lines when searching for food [15]. These examples highlight how collective behaviors emerge in different biological swarms, allowing them to solve complex problems or achieve collective goals more effectively than individual members could. By studying and imitating these behaviors, SI algorithms aim to capture and replicate the intelligence and problem-solving abilities observed in natural swarms.

It is important to indicate that the Boids algorithm, developed by Craig Reynolds in the 1980s [37], is considered one of the first fundamental techniques in the field of SI, despite its origins in computer simulation rather than in direct application to the real world. The algorithm simulates the flocking behavior of birds (or "boids") by defining three simple local rules that each boid follows: separation, which refers to the avoidance of crowding, alignment, which indicates adaptation to the average velocity of neighbors, and cohesion, which means getting closer to the average position of neighbors. Through the collective application of these rules, the Boids simulation was able to generate remarkably realistic flocking models, demonstrating the principle of emergence, according to which complex global behaviors can arise from simple local interactions. While the Boids algorithm was initially designed to model flocks of birds, its underlying principles have since been applied to a wide range of other swarming entities, such as schools of fish, colonies of ants, etc., making it the cornerstone of SI research and a key example of how computer simulations can provide valuable insights into the fundamental mechanisms that determine collective behavior in natural and artificial systems.

SI algorithms are attracting great attention and popularity in the research community and beyond. This is due to four main reasons, including flexibility and versatility, efficiency in solving nonlinear design problems, mimicking nature, and paradigm-shifting potential [14]. SI algorithms have a high degree of flexibility and can be adapted to solve a wide range of optimization problems, including continuous, discrete, constrained, and multi-objective problems. This flexibility appears in the efficient exploration of the search space and their application in diverse fields, from engineering design and planning to finance and machine learning. SI algorithms have demonstrated exceptional performance in solving problems with highly nonlinear and complex objective functions and constraints. Indeed, the inherent parallelism and decentralized nature of these algorithms allow them to efficiently navigate complex search spaces, making them well suited to problems with multiple local optima and difficult landscapes.

SI algorithms can capture the elegance and efficiency of natural problem-solving strategies, which have evolved over millions of years. This biomimetic approach to optimization has captured the imagination of researchers and practitioners because it represents a more intuitive and biologically inspired way to solve complex problems. The development of truly intelligent algorithms based on the principles of SI, capable of adapting, learning and making decisions autonomously, represents an important potential paradigm shift in the field of optimization and computational intelligence. Such algorithms could lead to breakthroughs in areas such as real-time decision-making, adaptive control and self-organizing systems, with far-reaching implications across various industries and applications.

SI algorithms are a diverse and numerous set of algorithms that share a common framework. Although the details and specific steps may vary depending on the algorithm used, there is a general overview that describes the typical phases involved in many SI algorithms [11].

1. **Initialize the population**: The algorithm begins by creating an initial set of agents or particles that form the swarm. These agents represent potential solutions to the problem studied.
2. **Set the stopping condition**: The algorithm specifies the ending criteria, which determine when the algorithm should stop the iteration and return the final result. This may be a maximum number of iterations, reaching a certain level of solution quality, or other criteria.
3. **Evaluate the fitness function**: Each agent in the population is evaluated by a fitness function, which quantifies how well each agent solves the problem. The fitness function measures the objective or quality of each solution.
4. **Exploration**: The swarm focuses on exploring the search space. Agents perform random or diverse movements to explore different regions and discover potential solutions. This exploration phase helps the swarm avoid getting stuck in local optima and discover new areas of the search space.
5. **Exploitation**: The swarm focuses on exploiting promising regions identified during exploration. Agents adjust their behavior to intensify research in these areas, refining solutions and converging on better solutions.
6. **Update and move agents**: The positions or states of agents are updated based on certain rules or heuristics. These rules take into account both exploration and exploitation factors. Agents communicate and interact with each other, exchanging information to guide their movements and decision-making. This interaction helps the swarm collectively navigate the search space and improve the overall solution.
7. **Returns the best overall solution**: At the end of the execution of the algorithm, the swarm returns the best overall solution found. This solution represents the best solution discovered by the swarm over the iterations. It is the result of the collective intelligence and cooperation of the swarm agents.

Although this framework provides a general overview, the specific implementation and variations of each phase may differ across different SI algorithms. The effectiveness of a particular algorithm depends on the problem at hand and the specific strategies used in each phase.

There are many SI algorithms studied in the literature (Fig. 3). The diversity of organisms in nature has created a diversity of algorithms that mimic the interactions and cooperation observed in various species. Some of the most popular SI algorithms include Ant Colony Optimization (ACO) [19], Particle Swarm Optimization (PSO) [7], and Artificial Bee Colonies (ABC) [1]. However, there are many other SI algorithms that have been developed based on different intelligent behaviors exhibited by animals such as pigeons, fireflies, bees, birds, bats, etc. [20, 26] (see Tab. 1).

Figure 3. What are some examples of various SI algorithms?

Table 1

How do some SI algorithms behave?

Algorithm	Nature's behavior	Simulation	Algorithm process
Particle Swarm Optimization (PSO) [7]	Bird flock behavior, where individual birds adjust their movement based on their own experience and that of their neighbors	Particles represent potential solutions in a multidimensional search space. Particles adjust their velocities based on personal best and global best positions	1. Initialize particles with random positions and velocities. 2. Evaluate the fitness of each particle. 3. Update the personal best position for each particle. 4. Update the global best position based on the personal best positions of all particles. 5. Adjust the velocities and positions of particles based on personal and global best positions. 6. Repeat steps 2–5 until convergence or a specified number of iterations. 7. Extract the best particle position as the final result

Table 1 cont.

Algorithm	Nature's behavior	Simulation	Algorithm process
Ant Colony Optimization (ACO) [19]	Ant foraging behavior, where ants make pheromone trails to communicate and find the shortest paths to food sources	Virtual ants deposit pheromone trails on the graph nodes to represent the quality of the paths. Ants probabilistically choose paths based on pheromone levels and heuristic information	1. Initialize the pheromone trails at the edges of the graph. 2. Generate ant solutions by probabilistically selecting nodes. 3. Update pheromone trails based on ant solutions. 4. Repeat steps 2 and 3 until convergence or a specified number of iterations. 5. Extract the best ant solution as the final result
Artificial Bee Colony (ABC) [1]	Foraging behavior of bees, where bees explore food sources and communicate the information to other bees in the hive	Bees represent potential solutions and explore the search space using local search and global search phases	1. Initialize the bees with random positions. 2. Employ onlooker bees to choose food sources based on quality. 3. Update the best food source based on the quality of the chosen food sources. 4. Employ employed bees to explore the search space around chosen food sources. 5. Employ scout bees to randomly explore new food sources. 6. Repeat steps 2 through 5 until convergence or a specified number of iterations. 7. Extract the best food source as the end result
Bacterial Foraging Optimization (BFO) [22]	Bacterial foraging behavior, where bacteria move to nutrient-rich regions using chemotaxis and communicate through signaling	Bacteria are represented as solutions and chemotactic steps are simulated to adapt their positions	1. Initialize a population of bacteria with random positions. 2. Evaluate the fitness of each bacterium. 3. Simulate the chemotactic steps to adapt the positions of bacteria. 4. Perform reproduction and elimination steps based on the fitness of bacteria. 5. Repeat steps 2–4 until convergence or a specified number of iterations. 6. Extract the best bacterium position as the final result
Firefly Algorithm (FA) [41]	Flashing behavior of fireflies, where fireflies attract each other based on the brightness of their flashes	Fireflies represent potential solutions and adjust their brightness and positions to attract other fireflies	1. Initialize fireflies with random positions and brightness. 2. Evaluate the fitness of each firefly. 3. Update the brightness and positions of fireflies based on attraction and movement rules. 4. Repeat steps 2–3 until convergence or a specified number of iterations. 5. Extract the firefly with the highest brightness as the final result

Table 1 cont.

Algorithm	Nature's behavior	Simulation	Algorithm process
Cuckoo Search (CS) [41]	Brood parasitism behavior of cuckoo birds, where cuckoos lay eggs in the nests of other bird species and the host birds accept or reject the eggs	Cuckoos represent potential solutions and eggs represent solutions in the search space. Cuckoos lay eggs (new solutions) in nests (existing solutions) and host birds (evaluation function) determine acceptance or rejection of eggs	1. Initialize a population of cuckoos with random solutions. 2. Evaluate the fitness of each cuckoo. 3. Generate new solutions (eggs) by modifying cuckoo solutions. 4. Replace eggs in nests based on the host bird's acceptance rule. 5. Perform local random walk to explore new solutions. 6. Repeat steps 2–5 until convergence or a specified number of iterations. 7. Extract the best cuckoo solution as the final result
Pigeon-Inspired Optimization (PIO) [26]	Pigeon homing behavior, where pigeons navigate and return home using landmarks and orientation cues	Pigeons represent potential solutions and use landmarks to update their positions in the search space	1. Initialize a population of pigeons with random positions. 2. Evaluate the fitness of each pigeon. 3. Update the positions of pigeons based on landmarks and orientation cues. 4. Perform local search to refine the positions. 5. Repeat steps 2–4 until convergence or a specified number of iterations. 6. Extract the best pigeon position as the final result
Wolf Pack Algorithm (WPA) [26]	Social hierarchy and hunting behavior of wolf packs, where wolves collaborate to hunt and maintain a territory	Wolves represent potential solutions and interact based on social hierarchy and hunting strategies	1. Initialize a population of wolves with random positions. 2. Evaluate the fitness of each wolf. 3. Update the positions of wolves based on social hierarchy and hunting strategies. 4. Perform local search to improve the positions. 5. Repeat steps 2–4 until convergence or a specified number of iterations. 6. Extract the best wolf position as the final result
Artificial Fish-Swarm (AFS) [35]	Collective behavior of schools of fish, where fish adjust their positions based on their movements, availability of food, and avoidance of predators	Artificial fish represent potential solutions and swim in the search space using individual and collective rules of behavior	1. Initialize a population of artificial fish with random positions. 2. Evaluate the fitness of each fish. 3. Update the positions of fish based on individual movements, neighbor tracking, feeding behavior, and predator avoidance. 4. Perform local search to refine the positions. 5. Repeat steps 2–4 until convergence or a specified number of iterations. 6. Extract the best fish position as the final result

Table 1 cont.

Algorithm	Nature's behavior	Simulation	Algorithm process
Grey Wolf Optimizer (GWO) [31]	Social hierarchy and hunting behavior of gray wolf packs, where wolves collaborate to hunt and maintain a territory	Wolves represent potential solutions and interact based on social hierarchy and hunting strategies	1. Initialize a population of wolves with random positions. 2. Evaluate the fitness of each wolf. 3. Update the positions of wolves based on the alpha, beta, and delta wolf positions. 4. Perform local search to improve the positions. 5. Repeat steps 2–4 until convergence or a specified number of iterations. 6. Extract the best wolf position as the final result
Butterfly Optimization Algorithm (BOA) [30]	Foraging behavior of butterflies, where butterflies explore the search space using random flights and pheromone-mediated movements	Butterflies represent potential solutions and adjust their positions based on random flights and pheromone traces	1. Initialize a population of butterflies with random positions. 2. Evaluate the fitness of each butterfly. 3. Perform random flights to explore the search space. 4. Update the positions of butterflies based on pheromone trails. 5. Perform local search to refine the positions. 6. Repeat steps 2–5 until convergence or a specified number of iterations. 7. Extract the best butterfly position as the final result

3.2. Design and usage process

Designing and using swarm intelligence (SI) algorithms [41] involves following a general framework described as (see Fig. 4):

1. **Problem formulation**: Clearly define the optimization problem that the SI algorithm will solve. Specify the objective function, decision variables, constraints, and any other problem-specific considerations.
2. **Algorithm selection**: Review existing SI algorithms and select the one that best suits the problem at hand. Consider the strengths, weaknesses, and applicability of the algorithm to the problem domain.
3. **Initialization**: Set the initial state of the swarm, which includes the positions or solutions of individual agents. The initialization must cover the search space adequately to ensure diverse exploration of potential solutions.
4. **Agent behavior and interactions**: Determine the behavior of individual agents (e.g., particles, ants, or birds) within the swarm. This involves defining how agents make decisions, update their positions, communicate with each other, and adapt their behavior based on local and global information.
5. **Objective evaluation**: Develop a method to evaluate the quality of each agent's solution based on the objective function. This evaluation feature guides the search process by providing feedback on the suitability or optimality of each solution.

6. **Swarm dynamics**: Define the rules that govern interactions and dynamics within the swarm. This involves determining how agents share information, exchange knowledge, and adjust their behavior based on the collective intelligence of the swarm.
7. **Parameter tuning**: Identify algorithm parameters (e.g., swarm size, convergence criteria, communication range) that affect algorithm performance. Perform sensitivity analysis or use optimization techniques to find appropriate values for these parameters based on the characteristics of the problem.
8. **Convergence analysis**: Analyze the convergence properties of the algorithm to understand its convergence speed and the quality of the solutions obtained. Use mathematical tools and techniques to prove convergence to globally optimal or near-optimal solutions under certain assumptions.
9. **Experimental validation**: Implement the algorithm and conduct experiments to validate its performance. Compare the algorithm's results with other state-of-the-art approaches or known optimal solutions to evaluate its effectiveness and efficiency.
10. **Improvement strategies**: Explore strategies to improve the performance of the algorithm. This may include integrating problem-specific knowledge, introducing adaptive mechanisms, exploring hybridization with other optimization techniques, or taking into account dynamic variations of the problem.
11. **Iterative improvement**: Based on the experimental results and information obtained, refine and iterate the algorithm design. Consider changes to agent behavior, swarm dynamics, parameters, or other aspects to improve the algorithm's convergence properties, efficiency, and solution quality.
12. **Benchmarking**: Compare the improved algorithm with existing approaches and benchmark it against relevant performance metrics. This analysis helps understand the strengths and weaknesses of the algorithm and provides insight into its applicability to different problem domains.

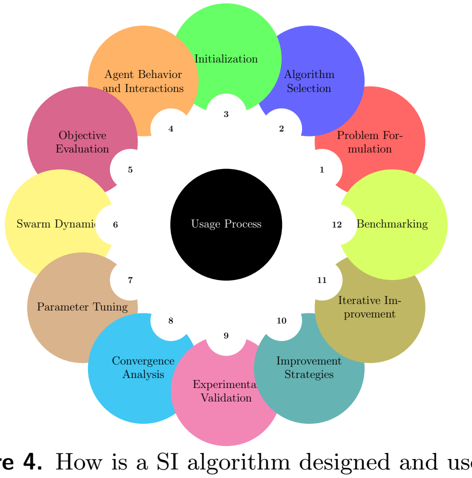

Figure 4. How is a SI algorithm designed and used?

3.3. Applications

Swarm Intelligence (SI) algorithms (see Fig. 5) have gained popularity due to their diverse applications in various fields. Some of the key applications of SI algorithms include machine learning, engineering, assignment, routing, networking, bioinformatics, etc. [1, 15, 19, 30, 31, 35].

Figure 5. How powerful are swarm intelligence algorithms?

3.3.1. Synergies (Tab. 2)

Table 2
How can SI algorithms create synergies with other scientific fields?

Field	Synergy examples
Machine Learning (ML)	In [7], the authors explore the challenges of high dimensionality and low sample size in cancer classification using microarray datasets. The study introduces an adaptive feature selection method that combines three filters (Chi-square, Information Gain and ReliefF) at first to reduce dimensionality and accelerate the training process. In the second stage, SI algorithms, particularly particle swarm intelligence (PSO), are used to select optimal features to improve classification performance. Finally, Ensemble learning techniques with different classifiers are applied in parallel with PSO to evaluate the model performance. The proposed method aims to improve the accuracy and efficiency of classification in cancer diagnosis and treatment

Table 2 cont.

Field	Synergy examples
	In [43], the authors investigate the use of two swarm intelligence algorithms, the Sparrow Search Algorithm (SSA) and the Whale Optimization Algorithm (WOA), to optimize the performance of an Extreme model Gradient Boosting (XGBoost) to predict the penetration rate (PR) of Tunnel Boring Machines (TBM) in complex geological conditions. Predicting TBM penetration rate is a critical task in metro construction projects because it helps engineers plan the construction schedule, estimate costs, and manage risks more effectively. The SSA algorithm mimics the foraging behavior of sparrows, while the WOA algorithm draws inspiration from the hunting techniques of humpback whales. In this study, researchers integrated these swarm intelligence algorithms with the XGBoost model, a powerful machine learning technique for regression and classification tasks. The objective of the SSA and WOA algorithms was to explore and identify optimal hyperparameter combinations for the XGBoost model, leading to more reliable and accurate predictions of TBM performance
Data science and Big Data	In [28], the researchers propose a big data text clustering algorithm based on swarm intelligence to address the limitations of current clustering algorithms and avoid the impact of disturbances on anomalous big data text clustering. They build a differential privacy model based on the characteristics of swarm intelligence, such as distribution and self-organization. The goal of integrating swarm intelligence principles is to provide a flexible data conversion platform to handle the incomplete information structure of big data, build a differential privacy protection model using KD tree partitioning to protect user location data while retaining data utility, and process location information via dimensionality reduction and clustering. In [12], the authors propose a Big Data-based model to address the limitations of traditional logistics systems and achieve more efficient management of e-commerce logistics warehouses, particularly through the optimization of goods allocation and warehouse routes. They used a Multi-Objective Particle Swarm Optimization (MOPSO) approach to optimize warehouse allocation and solve the problem of slow allocation of goods in warehouses. The study introduces a dynamic mutation probability formula to overcome the problem of convergence of local optima in traditional models. Ant Colony Optimization algorithms based on Genetic Algorithms (GA-ACO) were also used to develop a logistics warehouse path optimization model, thereby obtaining optimized logistics warehouse paths. All this to address the limitations of traditional logistics systems to meet the growing demands of e-commerce logistics, including efficient merchandise planning, convenient accessibility, equipment integration and optimization of merchandise management
Natural Language Processing (NLP)	In [21], the authors address the problem of topic modeling, which is a fundamental text analysis technique used to extract underlying topic structures or "topics" from a collection of text documents. Traditionally, topic modeling has been approached using single-objective techniques such as Latent Dirichlet Allocation (LDA), which optimizes a single criterion such as perplexity to discover topics. However, the authors argue that topic modeling is inherently a multi-objective problem, as there are several desirable properties that one would like to optimize simultaneously, such as coherence, coverage, and perplexity. For that, they propose a multi-objective optimization approach to topic modeling using a swarm intelligence algorithm called the Multi-Objective Artificial Bee Colony (MOABC) algorithm

Table 2 cont.

Field	Synergy examples
	MOABC is designed to simultaneously optimize the three objectives of consistency, coverage and perplexity, rather than aggregating them into a single objective function. This allows the user to choose the most appropriate compromise between the different objectives
Robotics	In [42], the authors present a novel decentralized and asynchronous robotic search algorithm based on Particle Swarm Optimization (PSO) to solve mazes and find targets in complex unknown environments. The proposed algorithm uses robots as particles in a PSO algorithm and equips them with toolkits to change course and avoid obstacles, as well as to memorize and reuse their best personal experiences to avoid dead ends. The algorithm is completely decentralized, requiring minimal communication between robots and no central synchronization. Robots move and update asynchronously. The fitness function is simply the inverse Euclidean distance to the target, requiring minimal knowledge of the environment on the part of the robots. The performance of the proposed algorithm remains constant even if the complexity of the search environment increases, unlike some other methods
Networking and distributed systems	In [44], the authors discuss the optimization of vehicle routing problem (VRP) in logistics network routing using an improved Pigeon-Inspired Optimization (PIO) algorithm. VRP is a fundamental problem in logistics and transportation that aims to plan the route of vehicles to meet customer demands while minimizing total costs. The study presents the new PIO algorithm, which exploits the strengths of the quantum evolutionary algorithm to improve global exploration and a Gaussian variation operator to improve local exploitation and prevent premature convergence. The improved PIO algorithm is designed in such a way that each individual contains information about customer points and routes. The objective is to optimize VRP in logistics networks to satisfy the ‱5R principle” (right quality, right quantity, right price, right time, right route) and minimize total logistics and distribution costs
Embedded systems	In [33], the authors discuss the application of multi-objective optimization techniques based on swarm intelligence to optimize the operation of industrial cooling towers to improve energy efficiency. Cooling towers are a crucial part of refrigeration systems in power plants and large buildings, used to dissipate heat and cool process water. Growing concerns regarding environmental sustainability and efficient use of energy and water resources justify the need to optimize the operation of cooling towers. The study proposes to use multi-objective optimization algorithms based on swarm intelligence, such as Multi-Objective Particle Swarm Optimization (MOPSO), to find the optimal operational set points for cooling towers. The objectives are to maximize the efficiency of the cooling tower while minimizing the overall power consumption of the refrigeration system, subject to operational constraints
Quantum computing	In [17], the authors present a novel approach that integrates quantum machine learning and deep self-learning techniques to solve the problem of emergency transportation management during the COVID-19 crisis. The authors first develop a quantum version of the OPTICS clustering algorithm, called Quantum OPTICS (QOPTICS), which aims to improve the computational efficiency of the classical OPTICS algorithm

Table 2 cont.

Field	Synergy examples
	They then propose in-depth self-learning approaches for two swarm intelligence algorithms, Artificial Orca Algorithm (AOA) and Elephant Herd Optimization (EHO). These deep self-learning variants, called DSLAOA and DSLEHO, use dynamic mutation operators to improve the efficiency of the original swarm algorithms. To leverage both efficiency and effectiveness, the authors further hybridize deep self-learning swarm algorithms with the QOPTICS algorithm, allowing the swarm algorithms to operate on a single identified cluster by QOPTICS. This hybrid approach is then applied to the real-world problem of optimizing emergency vehicle dispatch and patient transportation during the COVID-19 pandemic, with the goal of minimizing response times and ensuring adequate coverage in different geographic regions
Bioinformatics and computational biology	In [36], the authors propose a swarm intelligence-based hierarchical clustering approach to identify non-coding RNAs (ncRNAs) using a covariance search model. Covariance models (CMs) have been effective in identifying potential members of existing ncRNA families, but they have some drawbacks, such as being computationally expensive and limited to family-specific searches. Previous work used Hierarchical Agglomerative Clustering (HAC) to combine overlapping CMs into a single combined CM (CCM), but this eliminates structural information and dilutes sequence features as more families are added. The authors propose a novel approach that uses Particle Swarm Optimization (PSO) and Genetic Algorithms (GA) to select the best base pairs among multiple CMs to construct CCMs, with the aim of improving the performance of discernibility
Cloud computing	In [24], the authors present a novel method to improve task scheduling in healthcare services based on cloud computing in the IoT environment. This method is a new hybrid optimization algorithm called HPSOSSA which combines the strengths of Particle Swarm Optimization (PSO) and the Salp Swarm Algorithm (SSA). Task scheduling is a crucial challenge in cloud-based HCS because it impacts the timely satisfaction of user requests, service delivery costs, and service quality. For this, HPSOSSA algorithm is designed to solve this complex problem and then reduce factors such as lifespan, waiting time and resource utilization and finally improve healthcare service delivery
Distributed Constraint Optimization Problem (DCOP) [2–6]	In [23], the authors propose a new algorithm to solve the distributed constraint optimization problem (DCOP) using Particle Swarm Optimization (PSO). DCOP is a fundamental problem in multi-agent systems where agents cooperatively solve a constraint optimization problem. However, DCOP is NP-hard, making it difficult to solve large-scale problems in real time. The PSO process forms groups of agents, which are then used to solve the DCOP in a distributed and cooperative manner. The key innovation is to exploit swarm intelligence to discover appropriate optimality criteria, rather than imposing them a priori. This aims to provide a more flexible and adaptive DCOP algorithm capable of handling complex and large-scale multi-agent optimization problems. In [13], the authors present a novel Ant-based algorithm called ACO-DCOP for solving the distributed constraint optimization problem (DCOP). DCOP constitutes an important framework in multi-agent systems where agents must coordinate their decisions to optimize an overall objective function

Table 2 cont.

Field	Synergy examples
	The study presents new mechanisms within the ACO framework that are tailored to the DCOP context, including a way to calculate heuristic factors that capture local benefits and a method to calculate pheromone deltas that take into account the cost structure of DCOP. The study provides theoretical analysis showing that ACO-DCOP is an anytime algorithm, meaning it can return solutions of increasing quality over time

3.4. Limitations

It is important to consider a set of limitations and address them appropriately when applying SI in real-world applications. First, sensitivity to parameter settings and initial conditions. SI algorithms can be very sensitive to initial configuration and parameter settings. Slight changes in these factors can lead to suboptimal solutions or convergence failure, especially in large-scale systems [29]. Second, vulnerability to disruption. Swarms may be resilient to individual failures, but may be vulnerable to systemic disruptions such as environmental changes, resource depletion, or external attacks. These disruptions can destabilize the swarm, leading to disintegration, divergence, or oscillations [8]. Third, the balance between exploration and exploitation. Swarms must find a balance between exploring the space for new solutions and exploiting the best solutions found. There is a risk of getting stuck in optimal or suboptimal local regions if the swarm lacks diversity or adaptability [27]. Fourth, scalability. Although swarms can scale to large numbers of agents, the computational and communication costs can become prohibitive in large-scale systems. Efficient algorithms for coordination, decision-making and resource allocation are required, which can be difficult to design and optimize [8]. Fifth, social and ethical considerations. When using SI algorithms in social media or human-centric domains, there is a risk that swarm behavior will inadvertently reinforce the existing beliefs of individuals within the system. For example, if the Swarm algorithm favors or prioritizes certain types of content or interactions based on user preferences or prior engagement, this may lead to biased presentation of information. This bias can further reinforce the existing beliefs, opinions, or ideologies of individuals within the system. There is also swarm polarization, which refers to the division of individuals or groups into distinct factions with extreme or divergent beliefs. When SI algorithms reinforce existing beliefs and limit exposure to diverse perspectives, it can contribute to the creation of communities where individuals become more entrenched in their own views and less open to alternative ideas. This polarization can lead to increased animosity, reduced empathy, and a breakdown in constructive dialogue [8].

3.5. Challenges

Although SI algorithms have grown in popularity, they also expose several key challenges that researchers are actively addressing in this field [30, 31, 41]. First, despite the impressive performance of SI algorithms in practical applications, there is often a mismatch between the theoretical understanding of these algorithms and their observed effectiveness. Researchers are working to develop more rigorous theoretical frameworks to analyze the behavior and convergence properties of SI algorithms. Advances in mathematical modeling, complexity analysis and the development of new analytical tools are crucial to improve the theoretical foundations of SI algorithms and explain their empirical success.

Second, SI algorithms each have a diverse range of techniques and approaches, each with their own terminology and classification schemes. This lack of standardization can hinder communication and collaboration between researchers, as it can be difficult to compare and understand different algorithms and their underlying principles. Efforts are underway to standardize key terminology used in this area. This can facilitate better understanding, knowledge sharing and progress in the research community.

Third, the performance of SI algorithms often strongly depends on the choice of their parameters, such as the number of particles, the inertial weight or the rate of disappearance of pheromones. Finding optimal parameter configurations can be a difficult optimization problem in itself, because the performance of algorithms can be sensitive to the values of these parameters. Researchers are exploring various techniques, such as adaptive parameter control, machine learning-based methods, and self-adaptive mechanisms, to automate the parameter tuning process and improve the robustness of SI algorithms.

Fourth, although SI algorithms have demonstrated success in solving smaller-scale optimization problems, their applicability to large-scale, complex real-world problems remains a significant challenge. Scaling these algorithms to address large-scale problems with high dimensionality, many constraints, and massive search spaces requires new approaches and strategies. Researchers are investigating ways to improve the scalability of SI algorithms, such as hybridization with other optimization techniques, use of parallel and distributed computing, and development of problem-specific modifications.

Fifth, with the proliferation of various SI algorithms, researchers are often faced with the challenge of selecting the most appropriate algorithm for a given optimization problem. The choice of algorithm depends on factors such as problem characteristics, desired performance criteria, available computational resources, and specific application requirements. The development of guidelines, benchmarking frameworks, and decision support tools can help researchers and practitioners navigate the landscape of SI algorithms and make informed choices for their specific optimization tasks.

3.6. Future directions of research

Swarm intelligence (SI) algorithms have emerged as an important class of optimization techniques, inspired by the collective behavior of natural swarms. However, the field of SI algorithms faces several critical future research directions that researchers are actively investigating. First, conducting rigorous theoretical analysis is crucial to improve the understanding of the underlying principles, convergence properties and optimization capabilities of SI algorithms. This includes studying convergence behavior, analyzing complexity, and establishing formal mathematical frameworks for analyzing and comparing different algorithms. Second, researchers are exploring effective hybridization strategies that combine multiple SI algorithms or integrate them with other optimization methods, with the aim of achieving a better balance between exploration and exploitation, avoiding premature convergence, and improving the quality of solutions [24]. Solving complex optimization problems, such as high-dimensional, multimodal, and dynamic problems, is another key area of interest, as researchers adapt SI algorithms to address these challenges more effectively. Additionally, the development of a unified optimization framework for SI algorithms is a promising direction, as it could provide a systematic understanding of their performance differences, inspire the development of new algorithms, and facilitate the selection of appropriate algorithms for specific optimization problems. Finally, adopting a multidisciplinary approach by integrating knowledge from biology, psychology, computer science and engineering can lead to the creation of more generic and versatile optimization frameworks that draw on from various disciplines. By addressing these future research problems, the field of swarm intelligence algorithms can continue to evolve, providing more powerful and efficient optimization solutions for a wide range of real-world applications.

4. Conclusion

The paper provided an overview of Swarm Intelligence (SI) and its basic algorithms, highlighting their fundamental principles, design features and broad applications. It identified several common patterns or frameworks that contribute to the effective problem-solving capabilities of swarms, such as decentralized decision-making, use of simple local rules, redundancy and fault tolerance, and exploitation of indirect communication through the environment. These principles have inspired the development of various SI algorithms and distributed problem-solving approaches in areas such as robotics, computing, and logistics, providing new ways to address complex challenges in a decentralized and adaptive manner.

The paper also highlighted the need to address remaining challenges and explore promising future research directions in swarm intelligence. Improving the theoretical foundations, developing robust hybrid approaches integrating swarm intelligence with other optimization techniques, and improving the performance, simplicity, and versatility of swarm-based optimizers are identified as key areas for future research. By addressing these directions, future work on swarm intelligence can pave the way for even broader real-world applications and continued advancements in this dynamic and rapidly evolving field, unlocking the full potential of swarm-based solutions to solve complex optimization problems.

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ENERGY EFFICIENT AND QoS AWARE TRUSTWORTHY ROUTING PROTOCOL FOR MANET USING HYBRID OPTIMIZATION ALGORITHMS

Abstract *The security challenges in MANETs are particularly difficult to address. To assess the reliability of each mobile node, factors such as location, mobility speed, energy usage, transmission count, and neighbor list are considered. This research proposes the Intelligent Dynamic Trust (IDT) paradigm to enhance security in wireless networks. For secure routing, IDT combines beta reputation trust with dynamic trust. Performance analysis was conducted using Network Simulator 3.36, with metrics such as throughput, energy consumption, packet delivery ratio, jitter, end-to-end delay, packet loss rate, detection rate, and routing overhead. The results show that the proposed approach outperforms existing methods.*

Keywords MANET, levy flight centred shuffled shepherd dynamic source routing, firefly, whale optimization, energy consumption, secure routing, network simulator

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1. Introduction

The usage of mobile computing has seen an enormous increase in popularity over the years due to the development of new technologies and the desire for flexibility and simplicity in the workplace. A dynamic multi-hop wireless ad hoc communication network called a mobile ad hoc network (MANET) enables people and objects to easily connect without the need for any pre-existing infrastructure. Finding a route between the communication endpoints is the main issue in this type of network, which is made more difficult by node mobility, resource limitations, and channel access competition [9, 40]. To connect nodes that are unable to interact with one another directly, a routing protocol would be crucial in MANET. Quality of Service (QoS) indicators should be accessible in MANETs to provide prompt and reliable transmission of information and multimedia material. The absence of central administration, internal errors, and outside interferences all contributed to the difficulties in ensuring QoS. Connection breakdowns, high traffic rates, battery failures, process failures, and packet retransmissions are examples of internal problems [16]. A QoS-assured Mobility-Aware Routing (QMAR AODV) protocol based on AODV was proposed in [26]. It is essential to present an effective routing protocol in MANTs and demands an ideal QoS mechanism. There have been several types of research on routing optimization and communication models in MANETs, most of which undervalue the importance of mobility and its impact on QoS. In connection failures that result in packet loss and subsequent data retransmissions, node mobility is a crucial factor. In addition, route failures result in error packets, take additional time for network convergence, and need a new route discovery procedure if no alternative viable pathways exist. As a result, there is a corresponding increase in delivery latency and a corresponding decline in data quality [38].

Energy-efficient routing protocol

With new series of developing technologies, solutions have recently been offered in intelligent transportation systems, smart agriculture, retail utilities, and intelligent cities, to serve mankind. These solutions incorporate IoT networks, MANET, and other emerging technologies. These appliances will use a significant quantity of electricity. Saving energy is thus very important for MANET-IoT networks. Due to frequent changes in network architecture and the constrained energy resources of network nodes, route stability and mobile node energy capacity are the two most difficult problems in MANETs. Due to network congestion brought on by excessive duplicated traffic and connection failures, routing systems perform worse and use more energy. As a result, many strategies are being examined to address the problems caused by node mobility and energy failures in MANETs. To resolve these problems, a new routing algorithm of ant colony optimization (ACO) with ad hoc on-demand vector (AODV) [1] and MANET routing protocol [23] is proposed. Therefore, in the highly dynamic MANET environment, developing a plan that promotes energy efficiency is essential. Based on effective route failure detection [13], recommends the Energy Efficient Routing (EER) protocol. A new routing method was proposed to reduce failed communication in MANET. To maintain the least energy-consuming routes, a genetic algorithm-based AOMDV routing protocol is suggested in [30]. To extend the lifespan of the network and improve system performance, a delay-based energy-saving routing protocol for MANETs is presented in [39].

Data security in MANET

In the lack of infrastructure, mobile nodes wander within or outside the network. Security attacks including the grey-hole attack, Sybil attack, black-hole attack, jamming assault, and rushed attack might affect MANET. The effectiveness of the entire network is decreased by these attacks. Packets are lost or the link connection breaks when many assaults take place on the route. It results in less security and more power usage. A Hybrid Secure Aware Routing Protocol (HSARP) was presented to satisfy the QoS criteria. It encourages the proper distribution of power and security [21]. A novel GEO-TAODV routing protocol is utilized in MANETs [15] for data transmission. This method employs the GEO approach, a multiple-objective Meta heuristic optimization technique. Therefore, the protocol offers a stable and trustworthy method for data transfer in addition to an efficient one. In [11], the ANFIS idea with the Group Teaching Optimization Algorithm (GTA) is suggested for the evaluation of the neighbour's trust value for the trust-aware routing protocol. The mobility of nodes makes it challenging to maintain the proper QoS in the network due to frequent connection failures and high error rates. BAT optimization [27] and the improved animal migration optimization (IAMO) algorithm [18] were also used to increase the quality of service during data transmission to protect the MANET network.

Existing methods cannot be transferred to MANETS without being modified to carry out these protocols in various circumstances due to the basic differences between MANETS and wired networks. To ensure QoS in MANET, some new challenges specific to MANETS must be overcome, including node mobility, a lack of infrastructure, a lack of a centralised authority, multiple node functionality, energy limitations, erroneous link-state information, and constrained bandwidth. To create the route in various scenarios, there was intense cooperation between nodes. Routing optimization is a widely used technique to decrease the distance of data transmission and enhance the quality of service (QoS) of MANET applications. The data transmission channel from the source node to the destination node is referred to as routing. The most effective routing is a crucial problem in MANET since there are typically numerous options for the routing method. The clustering process, which causes the nodes to consume the least amount of energy for data connection, is one of the strategies that have been proposed for obtaining the best design. A trade-based strategy is required to solve the challenge of energy efficiency, either by compromising on energy use or other QoS metrics like delay, rate of transmission, or distance. Minimising the trade-offs as the network's population grows requires an optimised approach. Here, a hybrid strategy is set forth for energy optimization with little loss of other QoS factors. There is a significant chance that a packet will get dropped during communication, which can cause many security problems like confidentiality and privacy loss. The nodes might trick other nodes by sending misleading signals. As a result, the idea of trust management is born, which refers to building node reliability (i.e., trust). Devices are created with little computational and processing power due to the constrained power supply they operate on, consuming less energy. They are not required to adhere to all the security protocols for a strong secure network due to the limited power supply. Therefore, by selecting the optimum route for routing information, this problem can be solved. The DSR-optimized LF-SSO algorithm is employed in the study for the energy-efficient trust-based routing protocol.

2. Literature survey

The performance of QoS for users is directly impacted by the frequent changes in network architecture that the mobility of nodes in MANETs produces. To develop effective routing optimization techniques for a variety of traffic flows, network operators are essential. Khan et al. [20] proposed an algorithm that increases the reliable delivery of critical BAN data at the destination. We have performed extensive simulations in the OMNeT++-based simulator Castalia 3.2 to demonstrate the better performance of the proposed QoS-based routing protocol for reliability sensitive data in terms of lower network routing traffic (Hello packets) overhead, fewer reliability packets dropped, lower end-to-end delay (latency), fewer packets dropped due to media access control (MAC) buffer overflow and higher throughput in both stationary and movable patient scenarios. The scalability of the protocol is demonstrated by using two cases that simulate a 24-bed and a 46 beds real hospital environment with 49 and 93 nodes, respectively. El Dien et al. [6] proposed an energy-efficient and QoS-aware framework for transmitting multimedia content over WSN (EQWSN) is presented, where packet, queue and path schedules were introduced. It adapts the application layer parameter of the video encoder to the current wireless channel state and drops less important packets in case of network congestion according to the packet type. Finally, the path scheduling differentiates packet types/priorities and routes them through different paths with different QoS considering network lifetime. Simulation results show that the new scheme EQWSN transmits video quality with QoS guarantees in addition to prolonging network lifetime.

Muhammad Amjad et al. [2] proposed an energy-efficient routing protocol for heterogeneous WSNs to support delay-sensitive, bandwidth-hungry, time-critical, and QoS-aware applications. The proposed QoS-aware and heterogeneously clustered routing (QHCR) protocol not only conserves the energy in the network but also provides dedicated paths for real-time and delay-sensitive applications. The inclusion of different energy levels for the heterogeneous WSNs also provides the stability in the networks while minimizing the delay for the delay-sensitive applications. Extensive simulations have been performed to validate the effectiveness of our proposed scheme. The proposed routing scheme outperforms other state-of-the-art schemes in terms of delay performance. Faheem et al. [7] proposed the dynamic clustering-based energy efficient and quality-of-service (QoS)-aware routing protocol (called EQRP), which is inspired by the real behaviour of the birds mating optimization (BMO), has been proposed. The proposed distributed scheme improves network reliability significantly and reduces excessive packet retransmissions for WSN-based SG applications. Performance results show that the proposed protocol has successfully reduced the end-to-end delay and has improved packet delivery ratio, memory utilization, residual energy, and throughput.

Manisha Rathee et al. [35] proposed an ant colony optimization-based QoS aware energy balancing secure routing (QEBSR) algorithm for WSNs is proposed in this article. Improved heuristics for calculating the end-to-end delay of transmission and the trust factor of the nodes on the routing path are proposed. The proposed algorithm is compared with two existing algorithms: distributed energy-balanced routing and energy-efficient routing with node-compromised resistance. Simulation results show that the proposed QEBSR algorithm performed comparatively better than the other two algorithms. Kaur et al. [19] proposed an Optimized Energy Efficient and Quality-of-Service aware Routing Protocol (OEEQR) to achieve a longer network lifetime, energy efficiency, lower delay and high throughput. In the proposed protocol, the cost function with residual energy, distance and path loss as its parameters is optimized using the Particle Swarm Optimization (PSO) technique. The proposed cost function determines the best feasible next hop to send the data to the sink.

The QoS-aware routing optimization technique (QoS-ROA) was then introduced by Jiang et al. [14] to effectively handle the issue. The connection quality at the next instant is initially predicted using a wavelet neural network (WNN). Then utilize differential search (DS) to solve the proposed route optimization issue after converting it into a 0-1 knapsack problem. In Kalpana et al. [17], End-to-End Delay and bandwidth characteristics are tested with a Channel Aware AOMDV to offer QoS to the application layer. The Average Non-Fading Duration and Average Fading Duration will be used in the proposed strategy to analyze the channel fading. A QoS-aware routing with bandwidth and end-to-end delay is presented to decrease the control overhead. Different optimization-based MANET routing protocols have been put out for each of them to take into account various metrics and address certain issues. According to requirements for energy, stability, traffic, and hop count, Nabati et al. [28] presented a genetically based ad hoc on-demand distance vector mechanism. The ideal path is chosen using the Genetic Algorithm (GA) and Learning Automata (LA).

Multipath routing has been employed recently in WSN to provide scalable and dependable data transport. Even though several multipath routing methods have been put out, relatively few routing protocols have been specifically designed to provide QoS. The hybrid Particle Swarm Optimization and Cuckoo Search Optimization technique are used to cluster sensor nodes in Mohanadevi et al. [25] for a QoS-aware, multipath routing protocol. Using the cluster heads and multi-hop communication, the proposed protocol then selects several reliable pathways to send data. A novel protocol for sender-based responsive strategies on energy, mobility, and efficient routing for WSN is suggested by Dhanalakshmi et al. [4]. It covers a variety of issues in WSN communication, including energy optimization, energy balance, and packet routing in particular. This key goal is to suggest a safe and resource-conserving routing protocol that makes use of fuzzy rules and a node's trust values.

Dynamic topology, hidden terminal, multi-hop routing, exposed terminal issues, packet loss, mobility, and security threats are just a few of the difficulties faced by MANET. The set of instructions used to direct data packets from one node to another is known as a routing protocol. In Choudhary et al. [3], a flooding mechanism is used to broadcast the packet to determine the potential paths from the source to the destination nodes without affecting network conditions like energy, bandwidth, and link quality. In the reactive AOMDV protocol, an existing path fails when a node along the way moves out of range or becomes unreachable owing to low energy. The packet delivery ratio is also impacted by malicious node behaviour or outside noise interference. For packet transmission through numerous paths from source to destination, Saravanan et al. [36] presented trusted optimum path selection using channel and node-aware routing as a solution to this problem. To find numerous routes from source to destination, the AOMDV reactive routing protocol is employed. Then, either the many best paths are used to route packets from source to destination, or the delay factors associated with the multiple best paths are calculated, and the optimal path with the lowest delay factor is chosen for packet transmission. To improve path selection and energy efficiency, a new hybrid Zone-based Hierarchical Routing Protocol (ZHRP) based on the Dynamic Cuckoo Search (DCS) algorithm has been presented by Gopalan et al. [10]. A dynamic switching parameter has been used in the DCS algorithm to maintain the harmony between the global and local random walks.

By keeping numerous channels open between the communication nodes, MANET routing overhead can be minimized. In this manner, an alternative path can be easily adopted when one path fails without requiring a new route discovery. The link-disjoint, loop-free multipath AOMDV protocol is ideal for MANET. A node can monitor the strength of the received signal and take required action when the signal strength drops below a threshold level rather than waiting until a link fails. The reliable energy and link AOMDV proposed routing protocol takes into account both of these factors during route discovery and maintenance in Dsouza et al. [5]. Additionally, MANETs' dispersed operating model, which does not rely on centralized hardware like base stations, makes the guarantee QoS problem one of their biggest difficulties. Therefore, Quy (2022) [31] proposed a QoS-aware on-demand routing protocol (QoS-ADRP) for urban-MANET applications. The suggested protocol can operate in both adaptive and admission modes to increase the viability of the solution.

3. Methods

Mobile routers connected through a wireless link self-configure MANETs, which are wireless networks with an absolute topology. Due to its dynamic nature, routing is now seen to be the key issue with MANET. For effective routing in MANET, route discovery and the best route selection from a variety of routes are established. The main goal of this study is to choose the best route for MANET packet delivery. The mobility and resource limitations of nodes have a significant impact on the performance of mobile ad hoc networks (MANET). The development of a routing protocol that supports quality of service (QoS) in MANET is highly challenging since node mobility will affect connecting stability and node resource restrictions would cause congestion. It is necessary to develop the MANET protocol routing that can be adjusted for changes in the networking architecture to support QoS because, in particular, the frequent interrupting connection may decrease QoS performance in the high-speed node drive scenario. The suggested work's flow diagram is shown in Figure 1.

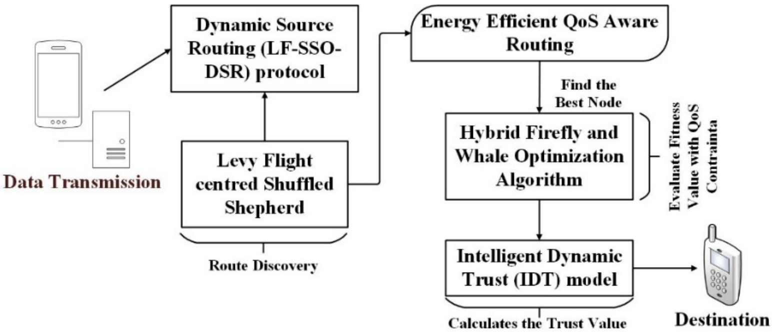

Figure 1. Flow diagram of the proposed work

The approach first identifies all possible paths between any source and any destination. Multiple routes are discovered using the route discovery scheme. With the use of the Levy Flight-centred Shuffled Shepherd Dynamic Source Routing (LF-SSO-DSR) protocol, which is used to apply an optimal path out of the multipath chosen based on QoS metrics, the transmission's best froute is chosen. Additionally, it has a high energy usage. Ad hoc network energy consumption is a constant challenge, which is what motivated the researchers to make use of bio-inspired algorithms and their fitness functions to assess node energy throughout the path-finding stage. To obtain the ideal values/fitness function for the objective parameter, hybrid firefly and whale optimization techniques also handle high energy consumption (i.e., energy). Somehow, there has been some exploration of the studies for resource limitations. The security challenges in MANETS present the most difficult assignment. The system and its linked consumer may be impacted by the adaptation of harmful elements, which causes communication issues. The reliability of each mobile node is assessed by taking into account factors such as the node's location, mobility speed, energy use, number of involved transmissions, neighbour list, etc. The research project then suggested the Intelligent Dynamic Trust (IDT) paradigm as a means of supplying security in wireless networks. For secure routing in mobile ad hoc networks, this paradigm combines beta reputation trust and dynamic trust.

3.1. Network model

The suggested system takes into account the network environment, which is organised and decentralized. The network's nodes can send and receive packets through many indirect hops. Assume there are N identical mobile nodes in the MANET network. The source node and destination node are allotted based on their respective distances, their ability to make linkages, and their routing paths. Each node can connect with its neighbouring nodes using a link l, while the nodes are separated by distance d and energy e. If the node i is the neighbour node of the node j, then the distance between these two nodes can be formulated as $d(i, j)$ and must be about the maximum transmission range of the node i, given as $d(i, j) < TR(i)$. Finding the best route while meeting QoS requirements and minimising energy consumption is known as QoS routing. Five evaluation factors are typically utilised as QoS limitations in IWSNs during actual factory production. They are bandwidth, cost, delay, delay jitter, cost, and packet loss rate. It is based on the supposition that neither the source nor the destination is malicious. Evil nodes do not cooperate among themselves, and all communication linkages are two-way. Additionally, the communication path is safe.

3.2. DSR routing mechanism

The routing pathways are determined at the time a source transmits a packet to the destination, making DSR the purest on-demand source routing system. Reactive routing protocol, or DSR, was specifically designed for use with multi-hop Adhoc networks of mobile nodes and allows the networks to function entirely on their own without centralised infrastructure. Each node in this style of routing stores the route data for recently taken routes by that node in cache memory. Route discovery and route maintenance are DSR routing's two key processes. A source node always verifies its route cache before attempting to send a packet to a destination node. The source node sends the packet along the available path if the route is open to the required destination node. Otherwise, the source node starts a route discovery process by implementing the LF-SSO method, which is done to give the nodes access to recognise and maintain the source routes to the destination nodes.

3.2.1. Optimal routing path discovery

To find a better link-quality path to transmit data from the SN to the DN, an optimal routing path discovery is used. The LF-SSO algorithm is used in this study to derive the best pathways from the chosen paths. The unique population-centred meta-heuristic LF-SSO method mimics the herding behaviour of shepherds. Shepherds put horses or other animals together to use their instincts to choose the finest pastures. The horses and lambs are chosen at random during the SSO algorithm's step size calculating process. Poor optimization is the result of this random selection. The proposed work substitutes a levy flight selection for a random selection to get over this problem. The LF-SSO algorithm is the term given to this algorithm.

First, a set of potential solutions is created, including sheep among other elements. The set of created potential solutions is expressed as in Equation (1):

$$\psi_j = \{\psi_1, \psi_2, \psi_3, \ldots, \psi_m\} \tag{1}$$

Herein, ψ_j signifies the candidate solution set; m implies the number of sheep $(m = h \times s)$; h signifies the number of groups and s implies the number of sheep in every group. Then, jth sheep's initial position in the f-dimension is articulated as in Equation (2):

$$\psi_j^0 = \psi_{\min} + \hat{r} \circ (\psi_{\max} - \psi_{\min}) \tag{2}$$

Herein, ψ_j^0 represents j^{th} sheep's initial solution, $\psi_{\min}$ and $\psi_{\max}$are bound by design variables, $\circ$ implies the element-by-element multiplication and $\hat{r}$ is the random vector ($\hat{r} \in [0,1]$). The fitness of each solution is then listed; here, the solutions of each candidate are taken into consideration as potential paths. As a result, the fitness of any solution is defined as the maximisation of path trust, minimization of EC, and minimization of path distance as expressed in Equation (3):

$$F_{opt} = \begin{cases} \max\left(\sum_{n=1}^{d} PT\left(N_n, N_{n+1}\right)\right) \\ \max\left(\frac{1}{N_n}\sum E_{res_n}\right) \\ \min\left(\sum_{n=1}^{d} dist\left(N_n, N_{n+1}\right)\right) \end{cases} \tag{3}$$

Where, $PT\left(N_s, N_{s+1}\right)$ and $dist\left(N_n, N_{n+1}\right)$ signify the path's trust and path's distance betwixt node N_n and N_{n+1}, correspondingly; $n = 1$ implies SN; d signifies the DN; E_{res_n}implies the node's residual energy. The solutions are arranged in ascending order based on the fitness values. To form the groupings, distribute the sheep to the group. The sheep are assigned to each group in descending order. The chosen sheep are known as shepherds, while the sheep that are well-fit and common in a herd are known as horses. Every shepherd's step-size $\left(S_{s_j}\right)$ is computed by choosing one amidst the horse and sheep as in Equations (4) and (5):

$$S_{s_j} = \omega \cdot L^y \circ (\psi_d - \psi_j) + \varpi \cdot L^y \circ (\psi_k - \psi_j) \tag{4}$$

$$L^y = t\left(-y\right), \quad 1 < y < 3 \tag{5}$$

Herein, ψ_d and ψ_k signify the horse and sheep chosen. L^y implies the levy flight distribution; $\omega$and ϖ imply the factors utilized to manage exploration and exploitation, correspondingly. These factors are enumerated in (6) and (7):

$$\omega = \omega_0 + \frac{\omega_{\max} - \omega_0}{I_{\max}} \cdot I \tag{6}$$

$$\varpi = \varpi_0 + \frac{\varpi_0}{I_{\max}} \cdot I \tag{7}$$

Herein, I implies the iteration; $I_{\max}$ signifies the maximal iteration.

The pseudo-code for the LF-SSO method, which is intended to find the best path, is shown in Algorithm 1. To achieve effective optimization, this algorithm executes good exploration in the initial iterations and better exploitation in the last rounds. Next, ψ_j the new position is enumerated as in Equation (8):

$$\psi_j'' = \psi_j^0 + S_{s_j} \tag{8}$$

If the fitness value ψ_j'' isn't worse analogized to ψ_j^0 fitness value, ψ_j's position is updated. Similarly, the fitness value of each path is assessed and compared to the corresponding old path. Repeating this process will continue until the best course is found.

Algorithm 1 Route Discovery with Optimum Routing Using LF-SSO

```
Input: Selected Routing Paths
Output: Optimal Routing path
Initialize the candidate solution ψ_j randomly
Determine the initial position using
  ψ_j^0 = ψ_min + r̂ ∘ (ψ_max − ψ_min)
Evaluate fitness
while (I = 0 to I_max) do
  Sort the solutions in ascending order // F_opt and form group
  Determine step size
    S_{s_j} = ω ∗ L^y ∘ (ψ_d − ψ_j) + ω̄ ∗ L^y ∘ (ψ_k − ψ_j)
  Generate new elements
    ψ_j^n = ψ_j^0 + S_{s_j}
  if (F_opt(ψ_j^n) ≥ F_opt(ψ_j^0)) then
    sheep position = ψ_j^n
  else
    sheep position ψ_j^0
  end if
end while
Return Optimal routing path
```

3.3. Energy consumption with QoS constraints

The inability of MANETs to support mobile networking devices due to a lack of adequate energy is a significant problem. The MANETs' packet forwarding is hampered by this deficit. The main issue with MANET has been identified as energy consumption, and it needs to be dealt with appropriately. Consequently, when the distance between nodes grows, so does the transmission power. When compared to when data is received, more energy is used during data transfer.

A node's energy consumption can be represented as in:

$$E_c = E_{TR} + E_R \tag{9}$$

Where the E_{TR} represents the transmission energy and the E_R represents the receiving energy. These energy values can be determined using the:

$$E_{TR} = D_t \cdot E_{ut} \cdot T_t \tag{10}$$

Where the D_t gives the rate in which the data is transmitted and the E_{ut}represents the total energy that is utilized for that particular transmission and T_t is the time taken for transmission.

$$E_{UR} = D_R \cdot e \cdot t_r \tag{11}$$

Where, E_{UR} is the total energy that has been utilized in the reception process and D_R is the rate of reception and t_r denotes the time of receiving the data. A MANET atmosphere with n the number of nodes in the set of $\{N\}$. All the nodes are considered to be connected with the nearest node through a link represented as L with a distance d. Nodes i and j are the nearest nodes and their distance is denoted by $d_{i,j}$ is considered to be lesser or equal to that of the range of transmission in node i as in (12):

$$d_{i,j} \leq T_{R(i)} \tag{12}$$

The total power applied at each link toward the path of data transmission from source to BS, which is evaluated by, is used to calculate the energy usage of a path:

$$E_{path_i} = \sum_{j=1}^{hop_i} E_{link_j} \tag{13}$$

For transmitting n bits of the data packet, energy application of a path E_{path} should be minimum when compared with essential lower energy E_{req}. Hence, the energy objective function f_E helps to reduce the overall power utilization on a path and is determined by:

$$f_E = \min\{E_{path_i}\} \tag{14}$$

Finding the path with the lowest energy consumption while also satisfying equations is the routing energy consumption optimization challenge for IWSNs. $C(e)$ can be represented by:

$$C(e) = E_c + E_R \tag{15}$$

In (11), $C(e)$ is the total energy consumption between two adjacent nodes, which is composed of E_c and E_b. E_c represents the energy consumption of data transmission, and E_b denotes the energy consumption of receiving information between two nodes.

3.3.1. Hybrid firefly and whale optimization algorithms

A unique hybrid firefly and whale optimization technique is developed to evaluate the node's energy through the path discovery stage with QOS restrictions to optimise the routing energy consumption of IWSNs with QoS constraints. In the subsequent stages of the algorithm, WOA does a local search instead of a global search, which can successfully find the routing path that complies with the QoS requirements.

Firefly algorithm for cluster head selection

The flickering lights of fireflies serve as the basis for firefly algorithm metaheuristics. A firefly swarm can be mapped to an optimal solution in the search space by moving to brighter and more desirable regions as a result of the intensity of the light. The firefly metaheuristic was chosen since it can offer the best solutions to multiobjective problems. This paper proposes and provides a novel fitness function that takes into account energy, end-to-end delay, and packet loss rate.

$$f(x) = \frac{(P_d/P_t) \cdot E_i^r/E_{init}}{\exp^{-e_d/e_m}} \tag{16}$$

Where, P_d is the number of dropped packets. P_t is the total number of packets sent. E_i^r is the remaining energy in the node i. E_{init} is the initial energy. The symbol e_d is the end-to-end delay and e_m is the maximum allowable delay.

Algorithm 2 Pseudocode for cluster formation and CH selection in firefly

```
Objective function f(x), x = (x_1, ..., x_d) T
Generate the initial population of fireflies x_i (i = 1, 2, ..., n)
Define light absorption coefficient γ
Determine the light intensity at each firefly position
while (t < MaxGeneration) do
   for i = 1 : n all n fireflies do
      for j = 1 : n all n fireflies do
         if (I_j < I_i) then
            Move firefly i towards j in d dimension
         end if
         Attractiveness varies with distance r via exp[−γr]
         Evaluate new solutions and update light intensity
      end for
   end for
   Rank the fireflies and find the best node as the cluster head
end while
```

The objective function of the firefly algorithm is embedded in the modulation of light intensity and the phrasing of the problem in terms of attraction. The preset light absorption coefficient and the light intensity are used to calculate the light intensity I can be computed based on distance r such that:

$$I = I_0 e^{-\gamma r} \tag{17}$$

Where, I_0 is the original light intensity. Approximating using Gaussian law we have:

$$I(r) = I_0 e^{-\gamma r^2} \tag{18}$$

The attractiveness $\beta$of a firefly is given in:

$$\beta(r) = \beta_0 e^{-\gamma r^2} \tag{19}$$

Where, β_0 is the attractiveness at $r = 0$. In two-dimensional space, the distance between two fireflies can be given by their Euclidean distance as $r_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$. A firefly i moves to a more attractive firefly j by:

$$x_i = x_i + \beta_0 e^{-\gamma r^2} (x_j - x_i) + \alpha \left(rand - \frac{1}{2} \right) \tag{20}$$

The nodes in each solution are represented in this work by binary values. The challenge in this type of encoding is between the real-valued vector space R^N and binary space $\{0,1\}^N$ and given by:

$$X_{ik} = \begin{cases} 1, & \text{if } rand() \leq \dfrac{1}{1 + \exp(-X_{ik})} \\ 0, & \text{Otherwise} \end{cases} \tag{21}$$

Where, $k = 1, \ldots, N$ and $rand() \sim U(0,1)$.

The best fireflies are chosen via tournament selection in the proposed firefly algorithm once the fireflies are ranked. As part of the WOA algorithm, the FA algorithm is used to update the whales' positions.

Whale optimization algorithm

The network lifetime of IWSNs can be efficiently extended for cost savings in the factory while maintaining QoS restrictions by utilising WOA to identify the optimal routing path with the least amount of energy consumption. A route's energy consumption is represented by the whale's fitness value in the routing energy consumption optimization problem with QoS restrictions. To determine the location of the leading whale, it is required to compute each individual's fitness before doing any additional CAWOA actions. Each person's fitness value is calculated using a formula (22). A fitness function is created to analyse the energy usage of routing, as demonstrated in:

$$fitness = \min \left\{ \frac{C(a) + DL(a) \cdot 1 + DJ(a) + PLR(a) \cdot PLC}{r \cdot B(a)} \right\} \tag{22}$$

In (14), $a = r(v_s, v_d)$ represents all routing paths that meet the QoS constraints from the node s to the node d in MANET. $C(a)$ is the energy consumption between two nodes, $DL(a)$ is the delay between two nodes, $DJ(a)$ is the delay jitter, $PLR(a)$ is the packet loss rate, PLC is the cost of packet loss, and $B(a)$ is the network bandwidth, r is the bandwidth factor. However, if a route does not adhere to the QoS requirements which include those for latency, delay jitter, bandwidth, packet loss rate, and cost it will be disregarded.

Secondly, the leading whale's position influences the update of each whale's position, and its formula is shown in:

$$W(gen + 1) = W(gen) - A.D \tag{23}$$

Where, A is another coefficient vector, which is calculated by:

$$A = \begin{cases} A_1 - \frac{(A_1 - A_2)(f_c - f_{avg})}{f_{\max} - f_{avg}} & f_c \geq f_{avg} \\ A_1 & f_c < f_{avg} \end{cases} \tag{24}$$

Where, f_c is the fitness value of the current whale, $f_{\max}$ is the fitness value of the leading whale. Accordingly, C_1 and C_2 are two constants and f_{avg} is the average fitness value of the population and A_1, A_2 are two constants. The inclusion of adaptive operators enables WOA to dynamically modify the parameters following the fitness value when the whale is feeding, hastening the algorithm's convergence.

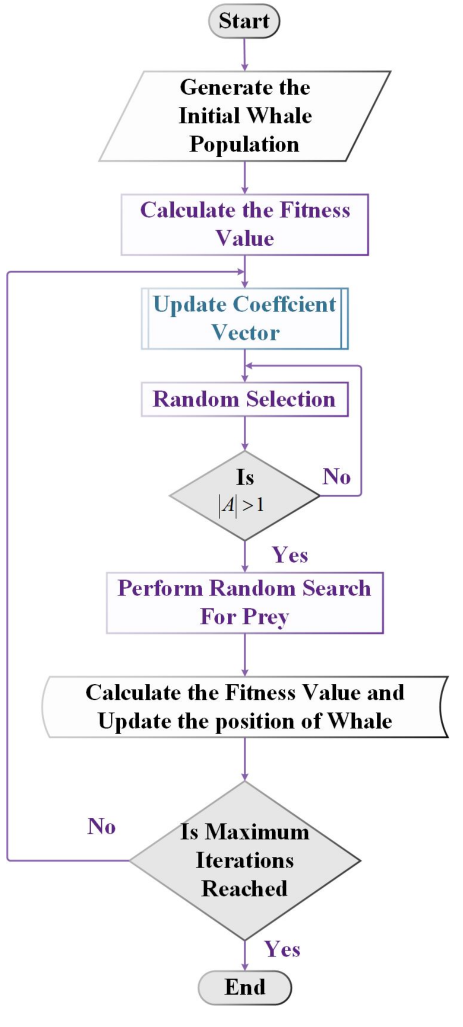

Figure 2. Flowchart of the whale optimization algorithm

The whale optimization algorithm's flowchart is shown in Figure 2. The location of the whale cannot always be updated by the position of the leading whale; occasionally, it must also be updated with the position of the partner to prevent hitting a local optimum when solving the MANET routing energy optimization issue under QoS restrictions. In particular, CAWOA's current mission is to conduct a random hunt for prey and determine the whale's future location. This operation is carried out while being influenced by the coefficient vector A. If $|A| > 1$, the random search behaviour of CAWOA increases the algorithm's capacity for global search, as demonstrated in:

$$D = |C \cdot W_r - W\,(gen)| \tag{25}$$

$$W\,(gen+1) = W_r - A \cdot D \tag{26}$$

Where, W_r is the random position in the whale population. To simulate the trend of the algorithm for lowering routing energy consumption, algorithm convergence speed, and the percentage of energy consumption acquired after optimization in multipath routing MANET. Somehow, there has been some exploration of the studies for resource limitations. The security challenges in MANETS present the most difficult assignment. The system and its associated consumer may be impacted by the adaptation of harmful elements, which causes communication issues.

3.4. Intelligent dynamic trust (IDT) for secure routing

In this study, an intelligent trust paradigm for secure communication termed intelligent dynamic trust (IDT) is suggested. The beta distribution is a popular technique for converting observed data from the evidence space to the trust space. Let s and f represent the total amount of positive and negative feedback in the evidence space about the target entity, then the trustworthiness t of a subject node is then computed as:

$$t = \frac{s+1}{f+s} \tag{27}$$

$$DT = Dynamic\ Trust\,(t, < t_1, t_2 >) \tag{28}$$

IDT is the combination of Dynamic Trust DT. The beta direct trust value is determined using intelligent agents and the Intelligent Dynamic Trust model. Here, the node trust is dynamically monitored by intelligent agents over a specific period. The suggested intelligent system presents each node's behaviour as a binary event. The distribution that is frequently used to represent the posterior probability of a binary event when using intelligent agents is utilised to model this binary event. Each node's dynamic trust model is assessed using the characteristics offered by the beta distribution that serves as a foundation. The family of probability density functions (PDFs) is a set of continuous functions indexed by two parameters α and β. In the beta reputation system, α is assigned as the number N_p of positive ratings plus 1 and β is assigned as the number N_n of negative ratings plus 1. Dynamic trust is initially the anticipation of a node acting pleasantly. The trustworthiness value is determined through future interactions and is calculated as:

$$\frac{\alpha}{\alpha+\beta} = \frac{N_p+1}{N_p+N_n} + DT \tag{29}$$

Where, p indicates the decay factor of forgetting can be employed to give new ratings more weight while progressively reducing the weight of previous ratings. The following formula is used to calculate intelligent beta reputation and dynamic trust value:

$$I = \frac{s+1}{f+s+2} + \frac{ds+1}{df+ds} + DT \tag{30}$$

Algorithm 3 Intelligent dynamic trust algorithm

1: **Initialization:** Let $T_V\,(n_1, n_2, \ldots, n_m)$ // T_V indicate trust value, $n_1, n_2, \ldots, n_m$ are nodes
2: **Step 1:** Every node n_i is considered a source node at different time durations
3: **Step 2:** Every node $n_1, n_2, \ldots, n_m$ are considered a source node in a different time duration (t_1, t_2)
4: **Step 3:** Send messages to the neighbour nodes.

$$NC = NC + 1$$

5: **Step 5:** Start the Scheduler Class to execute the simulation.
6: **Step 6:** Verify that the node is the destination node if it got the request from neighbouring nodes. Otherwise, if it is a destination, it transmits the acknowledgement to the nodes next to it.
7: **Step 7:** Compute the trust score for all the nodes using

$$t = \frac{s+1}{f+s}$$

8: **Step 8:** Compute the dynamic trust score for all the nodes using

$$DT = Dynamic\ Trust\,(t, < t_1, t_2 >)$$

9: **Step 9:** Compute the overall trust score for all the nodes using Equation (3)

$$\frac{\alpha}{\alpha+\beta} = \frac{N_p+1}{N_p+N_n} + DT$$

10: **Step 10:** **if**$(Minimum\ Value < Threshold)$
then detect the malicious node
else update the routing table with the new node
11: **Step 11:** Perform routing performance

The combination of IDT and dynamic trust. The trust value is determined dynamically using the proposed intelligent beta reputation model. The proposed work comprises a three-phase trust-based secure routing algorithm that evaluates trust scores, sets thresholds, and routes traffic according to trust values. The crucial component of dynamic trust-based secure routing is the focus of the proposed work. The fundamental objective of this work is the trust-based secure routing method. The proposed secured routing Algorithm 3 follows these steps.

The trust value is determined dynamically by the proposed secure routing technique. For each participating node in the network scenario, the trust values are computed at various periods. By obtaining an acknowledgement for their messages, the participant nodes verified the correct destination node. Similarly, the trust score and dynamic trust score for each node have been determined using Equations (27) and (28). In a network situation, threshold values are set by intelligent agents and verified against the dynamic trust scores of every node. Any node that has a dynamic score below a threshold must be regarded as malicious and should not be used for routing if the dynamic score is below the threshold. All other nodes with dynamic scores over the threshold are then included in the routing process.

4. Results

To assess the performance of the MRLAM routing system, which is compared with E-RARP, EEC-HO, TAGA, EHO-ETQRP, ETOR, and the proposed routing schemes, utilising the varied speed of node scenarios, extensive simulations have been carried out using the Network Simulator 3.36 simulator. One of the key criteria in research evaluating routing methods in MANETs is node speed. The efficiency of the proposed strategies' mobility awareness was assessed by taking mobility-related factors into account. The maximum speed in the RWP model was adjusted from 0 m/s to 10 m/s to specify the maximum waypoint speed of nodes.

4.1. Evaluation criteria of the proposed work

In the suggested work, experiments were carried out using the above-mentioned QoS parameters. The study observes the following results with QoS parameters by simulating the scenario created for analysing the impact of mobility on mobile network QoS parameters (throughput, average jitter, average end-to-end delay). Through some time simulations, the percentage of dead nodes, network longevity, energy consumption per node, and a fraction of alive nodes are all examined. This large simulation's goal is to assess the effectiveness of the suggested routing strategy, and the following metric is used to accomplish with:

Energy Consumption. The total energy used by all nodes for key transmission during the simulation is what is meant by this term. After each simulation, the energy consumption of each node is calculated while accounting for its initial energy.

The data transmission energy usage formula is:

$$E_{consumption} = \frac{E_{Total}}{Number\ of\ Packets\ successfully\ Transmitted} \tag{31}$$

where, E_{Total} is the total energy of the node which is 3600 mAh in the simulation model.

Jitter. The jitter is the variance in the transmission of messages from beginning to end. In the case of jitter evaluation, the message transmission time is very brief. The transfer delay time must be less than the necessary point value in the case of the jitter value. The following calculation yields the average value of jitter:

$$Jitter = D - (Q_{rs} - Q_{st}) \tag{32}$$

Packet Delivery Ratio (PDR). The number of packets received by the sinks at the destination divided by the number of packets generated by the application layer is the ratio. The following equation is used to calculate the packet delivery ratio for the proposed KF-MAC protocol:

$$PDR = \frac{Q_{rx}}{Q_{st}} \tag{33}$$

where, Q_{rx} is the received packet and Q_{st} is the sent packet.

Throughput. The quantity of successful messages sent over MANET is the network's throughput. Throughput is used to analyse messages sent in a given amount of time. The following equation yields the network throughput analysis:

$$Throughput = \frac{size_B \cdot T_{message\ Transmitted}}{T_r\,(simulation)} \tag{34}$$

where, B is the bit message, T_r is the response time.

Figure 10 shows a comparison of the KF-MAC protocol's throughput with those of the existing E-RARP, EEC-HO, TAGA, EHO-ETQRP, and ETOR protocols.

Number of Dead Nodes (NoDN). The metric displays all dead nodes after the simulation period.

Energy Cost per Packet (ECP). This indicator displays the average energy consumption as a percentage of the number of packets that were successfully received at the destinations. It is calculated as shown in the equation below:

$$ECP = \frac{Average\ Energy\ Consumption}{Total\ Packets\ Received} \tag{35}$$

According to Figure 3, all routing protocols spend more energy as the number of mobile nodes rises, which results in a larger network size since the mobile nodes in the network must process all of the routing packets. Figure 3 shows that from 14 to 18 nodes, all proposed protocols' energy usage is very similar. However, when the network size increases to 40 nodes, a noticeable change in energy consumption is apparent. Execution time is reduced by 3% in comparison to the current model, but energy usage is reduced by about 20%.

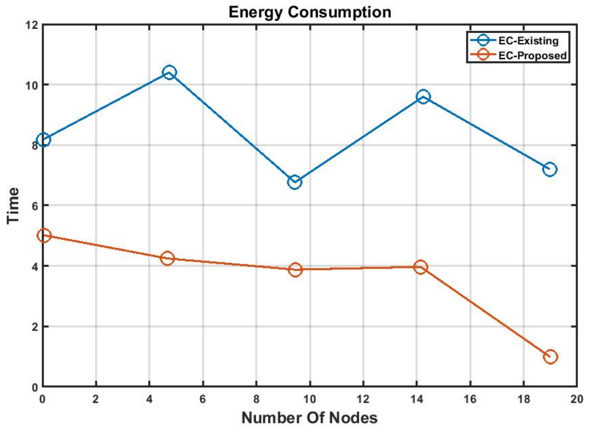

Figure 3. Energy of network nodes vs time

The graphs of the routing energy usage optimization are shown in Figure 4. This illustrates how the suggested optimization converges more quickly than the existing algorithms, which have slow convergence rates. While FFWHO gets the best routing solution with a 0.38 J energy consumption and a faster convergence speed, the suggested technique is locked in premature convergence. At the start of the iteration, this achieved lower routing energy usage than other algorithms, and this trend was maintained until the algorithm's termination.

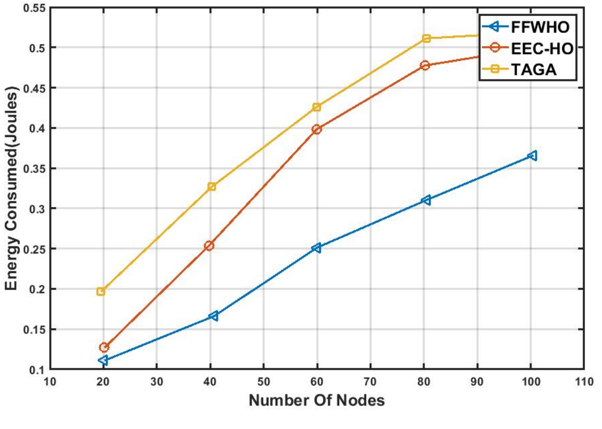

Figure 4. Energy consumption analysis

The end-to-end delay between the current and suggested algorithms, with the number of nodes, is represented by the plot in Figure 5. It has been determined that the suggested technique improved network performance and recorded the smallest end-to-end delay at time 0.0015. This authentication method causes a delay, which lasts longer in the event of an attack. In particular, it is the reason for attacks that perform poorly in terms of security once the path has been set.

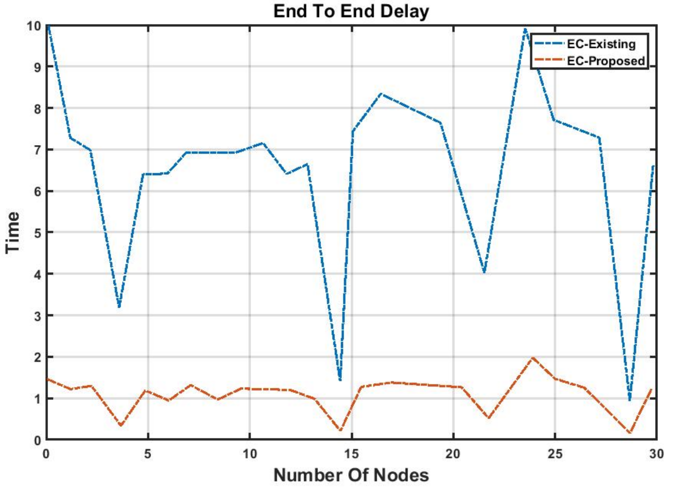

Figure 5. End-to-end delay vs time

The DSR application is connected between the two nodes in this example, node 9 is delivering packets to node 3. Delay is introduced during transmission, and the average end-to-end delay varies with the change in speed. Figure 6 displays the average end-to-end delay variation concerning speed. Figure 6 shows that the average end-to-end delay is very low while the speed is low, or 0.02926 s at the speed of 10 m/s, but it grows as the speed increases, becoming 0.11596 at the speed of 30 m/s. The movement of node 3 affects the average end-to-end delay since the mobility model is a random waypoint.

Figure 7 shows that the jitter is initially very low, or 0.01129 seconds when node 5 is moving at a speed of fewer than 10 m/s. As speed increases, however, the jitter likewise rises, reaching 0.06792 seconds at a speed of 15 m/s. The reason for this is that either the entire signal is broken up into chunks of data and conveyed to a receiving device for assembly, or the data is divided up into manageable "packets" with headers and footers that indicate the correct order of the data packets. Jitter makes synchronisation difficult and makes it challenging for the receiving unit to accurately assemble the incoming data stream. As a result, throughput is lower and jitter is greater at high speeds.

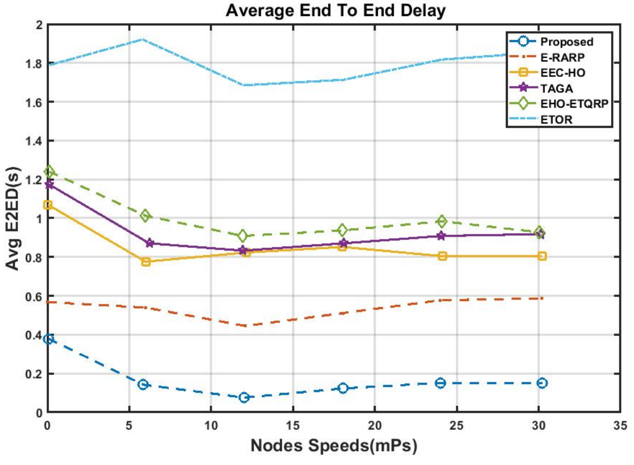

Figure 6. Average end-to-end delay

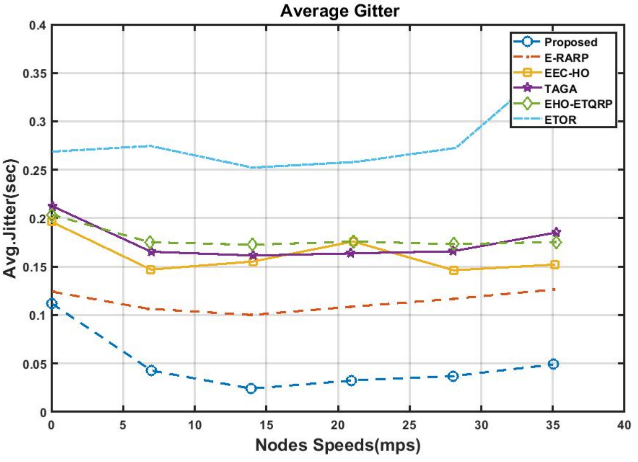

Figure 7. Average jitter vs nodes speed

The total packets dropped as a measure of packet loss and transmission failure is another QoS metric that is compared in this scenario and is shown in Figure 8. The findings show that the suggested reduces the overall number of packets dropped and achieves the lowest number of dropped packets across all scenarios. When compared to LS-SSO-DSR, which is obtained at 10 m/s, the suggested minimises the number of missed packets up to 329 packets. Using energy and mobility-aware approaches, the MBMA-OLSR outperformed the traditional scheme and reduced the number of packets missed, enabling it to successfully transfer the packets between source-destination pairs. The rising number of missed packets in LS-SSO-DSR is ascribed to the lack of mobility awareness support, which would have allowed users to choose the optimum paths, particularly in the event of a link failure brought on by node mobility.

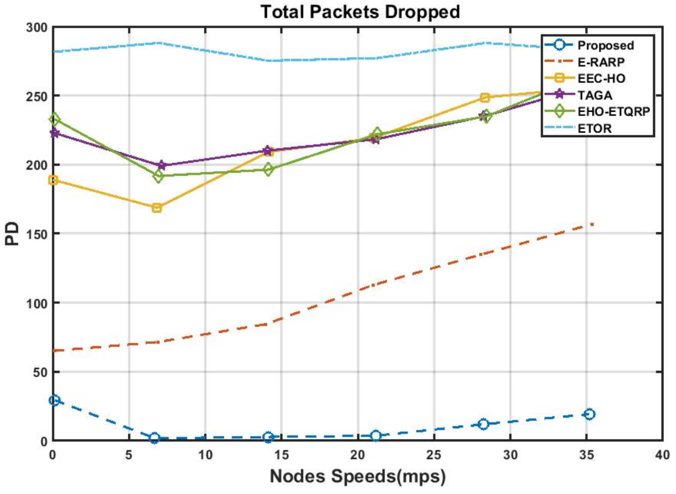

Figure 8. Packets drop vs nodes speed

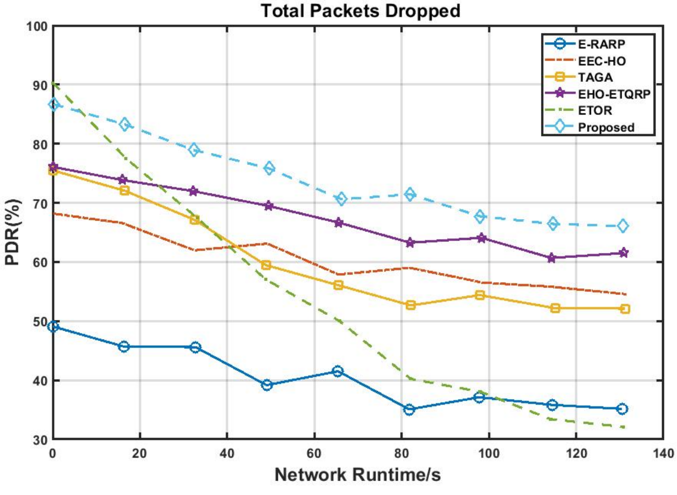

Figure 9. Packet delivery ratio vs network runtime

As the network size grows, the PDR of DSR gradually declines, as illustrated in Figure 9. Unlike other figures, this one compares the performance improvement brought on by the hybrid nature of LA-SSO-DSR by including graphs for reactive routing protocols E-RARP, EEC-HO, TAGA, EHO-ETQRP, and ETOR as examples. Regardless of network size, this surpasses all other approaches and successfully raises the PDR. Maintains a PDR of at least 83% as the desired level of quality of service for consistent data transmission. As a result, the routing protocol maintains a greater

PDR and lower delay than previous multipath systems by choosing nodes with high residual energy, low congestion levels, and lengthy idle times.

In terms of node speed and routed data packets, Figure 10 shows the throughput performance parameter of MANETs using E-RARP, EEC-HO, TAGA, EHO-ETQRP, and ETOR. Figure 3 shows that at 10 m/s (metre per second), throughput is 2 bits and that as speed increases, throughput decreases. For a 25 m/s node speed, the LA-SSO-DSR protocol outperformed EEC-HO by up to 14% in throughput. Finally, the outcome demonstrates that the suggested convention performs better.

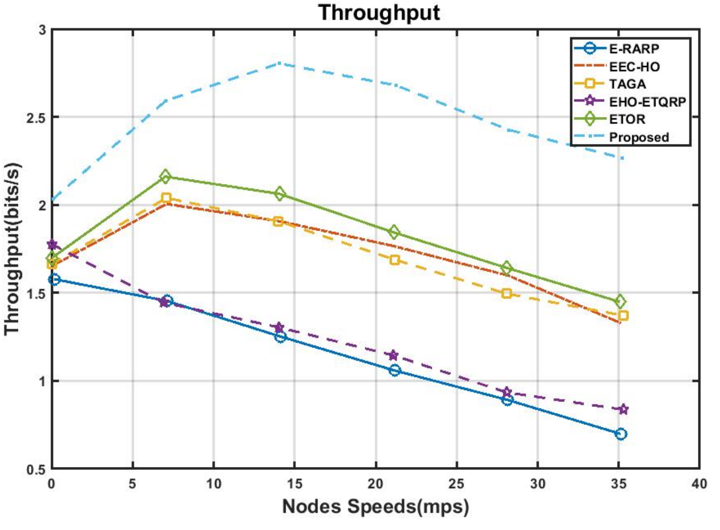

Figure 10. Throughput vs nodes speed

Figure 11 illustrates that there are very few interactions between nodes and that the impact of dynamic weight on integrated trust value is near $\phi = 0.1$. The trust value is more dependent on indirect trust when there are fewer interactions between nodes, and as interaction times increase, the effect of dynamic weight on integrated trust value gradually moves towards $\phi = 0.9$. This indicates that the integrated trust value metric measure is more dependent on direct trust as the number of contacts between nodes increases. The acquired results are consistent with the earlier theoretical study. The accuracy of trust measurement can be improved by dynamically adjusting the weight factor following the volume of node interactions.

Figure 12 illustrates how many dead nodes there are. This straightening results from duplicate pathways created by dying nodes close to the target. However, this straight line emerges much later in the figure for other approaches, indicating a longer lifetime. The chart makes it evident that the clustering with the gateway method has 50% of nodes still alive after 275 rounds, but 50% of nodes in both other schemes die considerably sooner due to significant energy consumption at roughly 65 rounds.

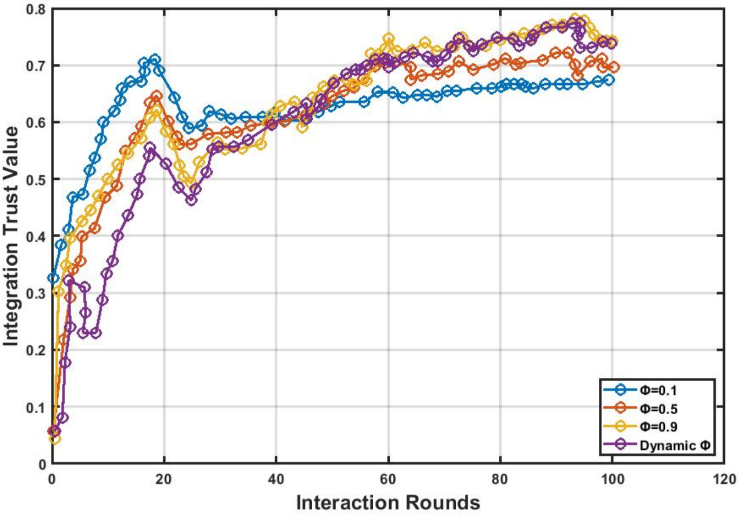

Figure 11. Effect of dynamic weights on integrated trust value

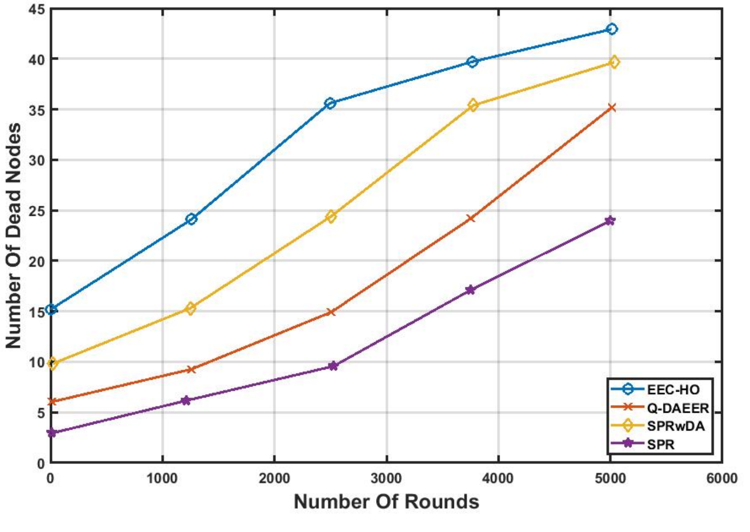

Figure 12. Number of dead nodes vs number of rounds

Figure 13 displays the detection rate for several trust models, and can see how the DTEM performed for Data 1, Data 2, and Data 3. Data 1 and 2 are subject to numerous attacks, therefore when the number of malicious nodes rises, the detection rate rapidly declines, however, data 3 maintains a high detection rate. As a result, the

IDT is a reliable trust evaluation model that can recognise many types of malicious nodes and may be dynamically altered to meet the unique needs of the network.

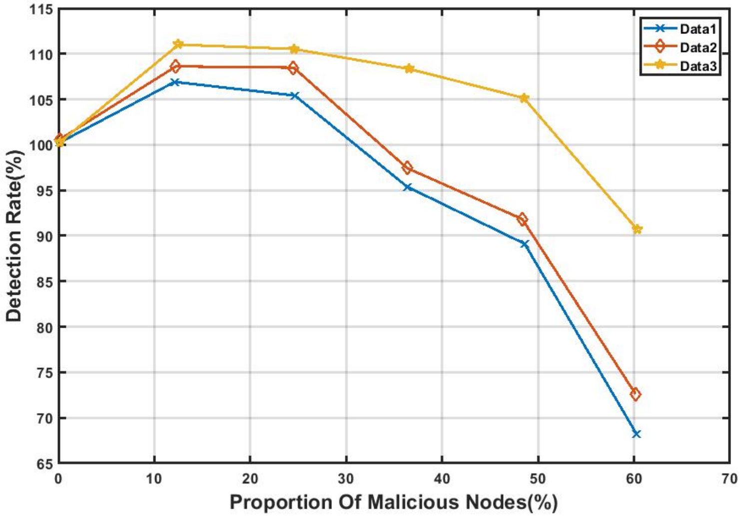

Figure 13. Proportion of malicious nodes

5. Discussion

The effectiveness of the optimised dynamic source routing protocol (DSR) for MANETs is examined in this article. The LF-SSO algorithm is used to modify the conventional DSR algorithm to determine the best routes between the communication nodes. In this work, the performance of the suggested technique is compared to the performance of the DSR protocol when there are malicious nodes present. Describes the variation in trust scores between the current and proposed systems. The proposed system outperforms the current system. This is because dynamic trust value calculation and a clever reputation system are used. In the initial deployment region of 1000 m $\times$ 1000 m, the network is clustered with 100 nodes. In terms of node speed and routed data packets, the article finds the throughput, energy consumption, jitter, packet delivery ratio, the number of dead nodes, and energy cost per packet performance parameter of MANETs is estimated using comparison techniques of E-RARP, EEC-HO, TAGA, EHO-ETQRP, and ETOR. The proposed technique has a 25 m/s node speed for protocol also the technique outperformed EEC-HO by up to 14% in throughput.

Subbaiah et al. [37] provided a reliable and energy-efficient healthcare system routing technique to balance QoS and power consumption. Performance metrics include routing overhead, energy consumption, end-to-end latency, throughput, scalability, and transmission error. According to testing, IBOLSR uses less energy and has a longer lifespan than OLSR, EAOLSR, and BOLSR. The simulation results demonstrate that the proposed algorithm outperforms other existing algorithms. In tests, the proposed work shows a 79% less Average End-to-End Delay compared to other existing algorithms. Rachna Jain et al. [12] study illustrates that the throughput of proposed LD-OLSR is increased by 13% over conventional OLSR with 120 s of simulation time.

Rama Rao [33] proposed FCS-based multipath selection shows that the proposed QoS aware routing protocol performs better than the existing routing protocol with a maximal energy of 99.1501 and minimal delay of 0.0554. Later, Kebebew Ababu Yitayih et al. [40] proposed quality of service (QoS) supporting the MPR selection approach and a new lower maintenance clustering approach for minimizing the overhead of the network. The study selects a minimum number of MPR, and it minimizes the number of retransmitted control packets of a network into 61.12. R. Lavanya et al. [22] proposed an energy-efficient and optimal QoS-aware multi-path routing protocol based on EHO (Elephant Herding Optimization) algorithm and trust called EHO-ETQRP for IoT. Based on the energy and trust update, the secure nodes are selected and which improves secure communication. The simulation result proves that the proposed routing protocol is used to increase the delivery ratio, energy efficiency and network lifetime, which are the network-related QoS parameters. Rajakumar Ramalingam et al. [34] proposed the ad hoc on-demand distance vector protocol (AODV) is used and analyzed based on MANET's QoS (Quality of Service) metrics. The QoS metrics for MANET depend on delay, bandwidth, memory capacity, network load, and packet drop. This proposed algorithm stagnates in a lifetime of 4 ms.

Mamatha et al. [24] took an algorithm that takes place from 210 to 230 bits/s with 25–175 time intervals. Veguru Gayatri et al. [8] overcome the limitations of slow convergence and premature resolution of Quality of Service using multicast routing problems particle swarm optimization algorithm (PSO) and genetic algorithm (GA). The value of BER decreased for all techniques as the node increased. The suggested work displays a BER of 8% at the outset. Mobile nodes dynamically enter and exit the network often, resulting in unstable network topology in MANET. As a result, maintaining a stable network becomes a challenging task. Path preservation, battery life, safety, dependability, and unexpected connection characteristics are the major issues in MANET.

Rajathi et al. [32] presented a cluster coordinator-based CH election mechanism (CCCH). The comparison result proves that the proposed algorithms' performance is far better than the others in all evaluation metrics, such as energy consumption, packet delivery ratio (PDR), and the number of CH changes. K. Nirmaladevi et al. [29] proposed Selfish Node aware Trustable and Optimized Clustering-based Routing (SN-TOCRP) follows hierarchical clustering for creating node clusters. This achieves improved results with a Packet delivery ratio of 96%, a loss ratio of 0.045%, an average delay of 0.325 ms with throughput is 76 Kbps, an end-to-end delay of 0.425 ms and an energy consumption of 88 MJ. The comparison results prove that the proposed system performs better than the existing approaches in all evaluation metrics.

Limitations

The comparison highlights the design of efficient routing protocols satisfying specific QoS metrics for a specific application using a specific routing technique. Moreover, WSNs need to provide different levels of Quality of Service (QoS) based on the different demands of various types of applications. The proposed framework still outperforms the malicious node scenarios based on the stated performance metrics. However, the study does not undertake any attack-related results, this tends to improve the robustness of the study.

6. Conclusion and future scope

Due to the lack of centralised control, Mobile Adhoc Networks (MANET) experience more network disconnections as a result of energy depletion issues. The main difficulties that MANET networks encounter are their dynamic topologies, energy constraints, bandwidth limitations, varying links, higher loss rates, high delay, and jitter, as well as the lack of centralised control and their limited physical security. However, node information must be continuously maintained for routing. So, reactive routing protocols (also known as on-demand routing protocols) were used to overcome these constraints and improve the routing performance in MANETs. The majority of Adhoc networks favour these reactive protocols. As a result, the research suggested using the Levy Flight-centred Shuffled Shepherd Dynamic Source Routing (LF-SSO-DSR) protocol to choose the best path out of a group of paths that were chosen based on QoS parameters. The main and crucial problem with MANET, aside from the routing technology, is how it operates under energy constraints. The batteries' issue with energy depletion has a big impact on how well the network functions. Because of this, hybrid firefly and whale optimization methods (FFWHO) successfully find the routing path that complies with QoS requirements. The research project then suggested the Intelligent Dynamic Trust (IDT) paradigm as a means of supplying security in wireless networks. The simulation moves following the mass mobility model to evaluate the performance of the energy-efficient-based QoS-aware routing protocol. Performance analysis of QoS metrics is evaluated in Network Simulator 3.36 simulation. Several performance metrics, including throughput, energy consumption, packet delivery ratio, jitter, end-to-end delay, packet loss rate, detection rate, and routing overhead, are used to assess the suggested approach. This outcome shows that the suggested strategy works better than other cutting-edge approaches. The simulation results demonstrate that in terms of routing energy consumption, convergence speed, and optimization capability, the proposed routing algorithm based on the optimization algorithm outperforms existing methods. It follows that the adoption of LA-SSO-DSR with a hybrid optimization approach can successfully lower the MANET's routing energy consumption.

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AN IMPROVED CONTEXT-AWARE SENTIMENT ANALYSIS OF STUDENT COMMENTS ON SOCIAL NETWORKS BASED ON ChatGPT

Abstract *The widespread use of social networks has provided a variety of active, dynamic, and popular platforms for students to express their opinions and sentiments. These data are increasingly being exploited and integrated into university information systems to better govern and manage universities and improve educational quality. The analysis of such data can offer valuable insights into student experiences and attitudes towards various educational aspects including courses, professors, events, and facilities. However, automatic opinion mining in this context is challenging due to the difficulty of analyzing some languages such as Arabic, the variety of used languages, the presence of informal language, the use of emoticons and emoji, sarcasm, and the need to consider the surrounding context. To deal with all these challenges, we propose a novel approach for an effective sentiment analysis of student comments on the X platform (Twitter). The proposed approach allows the collection of student comments from public Twitter pages and automatically classifies comments into positive, negative, and neutral. The new approach is based on ChatGPT capabilities, supports three languages: English, Arabic, and colloquial Arabic, and integrates a new scoring method that measures both the positiveness and subjectivity of student comments. Experiments performed on simulated and real public Twitter pages of five Saudi high education institutions showed the performance of the proposed tool to analyze and summarize collected data automatically.*

Keywords sentiment analysis, educational social networks, student opinion mining, Lexicon-based approach, transformer-based methods

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1. Introduction

Social media platforms, such as "Facebook", "Twitter", "Instagram", "LinkedIn" and "TikTok" have emerged as popular spaces where people can freely express their thoughts, opinions, and personal experiences. These platforms offer users an open and free environment to create profiles, establish connections with friends, communicate with family members, and share several types of online content including documents, photos, videos, and many other online resources. Social platforms enable boosting interactions and engagements in the network by allowing users to easily like, comment on, or share each other's posts. The large number of users and the wide range of activities on these platforms make them valuable resources across various domains. For example, in the marketing domain, social networks provide a powerful platform for businesses to promote their products or services [9, 19]. In healthcare, social networks are utilized to disseminate health-related information and connect patients with support groups [6, 16].

In the educational domain, social networks have been extensively used by educational institutions such as schools, faculties, colleges, and universities to improve their digital presence and engage with their students, alumni, and broader communities [12, 13, 20]. These pages can be either official, created by the educational institutions, or unofficial, created by other parties. In any case, these pages on social networks allow students to express their feedback on various aspects of their academic journey, including courses, professors, campus facilities, and overall university experiences. Data collected from these platforms are crucial for universities to understand student thoughts, identify areas of improvement, and enhance the overall educational experience [20]. For example, identifying the opinion of students regarding course content allows universities to identify the courses that need new evaluations and improvements. This task is referred to as **sentiment analysis** (or **opinion mining**) of student comments.

The sentiment analysis of student comments on social networks presents several challenges that must be addressed to accurately detect the emotional tone expressed in collected comments. One major challenge is the unstructured and informal nature of student comments on social media platforms. These comments often include slang, abbreviations, emojis, and other informal language constructs that complicate the text processing and analysis stage. The unstructured textual comments require comprehensive pre-processing tasks to organize them into a structured format to facilitate their effective processing by learning algorithms. Another significant challenge is the inherent ambiguity and subjectivity of natural language. Sentiment analysis algorithms must discern the context and nuanced meanings of words to accurately detect the correct sentiment. The same term can convey different sentiments depending on its context. Texts containing subjective opinions often do not clearly indicate a positive or negative sentiment and usually require sophisticated natural language processing techniques to effectively interpret contextual meanings. Another critical challenge in sentiment analysis is the difficulty of processing texts written in languages with complex morphological structures or texts written in colloquial languages. For instance, the Arabic language presents unique challenges due to its rich morphology, special characters, and right-to-left writing direction. Similarly, colloquial languages or regional dialects pose significant challenges due to their informal nature and regional variations. These dialects often include specific terms, idiomatic expressions, and regional variations that are not well-represented in formal language corpora. Existing sentiment analysis tools, that can be effective for standard versions of languages, often do not perform well with Arabic and colloquial languages. Advanced language processing techniques are required to handle the complexities of these languages and accurately analyze sentiments in diverse linguistic contexts.

To deal with all the discussed challenges, we propose in this paper an innovative approach, centered around an improved context-aware sentiment analysis method, able to effectively collect, analyze, and classify student comments on Twitter public pages related to higher education institutions into positive, negative, and neutral categories. The proposed approach uses automated techniques to gather a substantial volume of student comments from Twitter pages and then pre-process the unstructured textual comments to facilitate a comprehensive analysis of student sentiment. The proposed approach has been designed to support formal and informal languages to better recognize student opinions and thoughts. By combining the strengths of lexicon-based and transformer-based methods, the proposed approach builds sentiment polarity scores for student comments through three phases leveraging both TextBlob and ChatGPT capabilities and taking into account language nuances and subjectivity of student comments.

The major contributions of this paper can be summarized as follows:

- Design of a New Hybrid Sentiment Analysis Model. We introduce an innovative hybrid sentiment analysis model that effectively detects sentiments in student comments collected from social networks. The model combines the strengths of transformer-based methods (such as ChatGPT) and lexicon-based approaches (such as TextBlob), providing a comprehensive and accurate sentiment detection framework.
- Exploration of Transformative Models for Complex Languages. We explore and evaluate the capability of transformer models, such as GPT-turbo-3.5, in enhancing sentiment analysis for languages with complex morphological structures and non-rich corpora, such as Arabic. We also examine their effectiveness in processing text written in colloquial languages, addressing the challenges of informal and region-specific dialects.
- Comparative Analysis of Model Effectiveness. A comparative analysis of the proposed hybrid model against conventional machine learning, deep learning, and transformer-based models is conducted. The comparison demonstrates the superior performance of the hybrid contextual-based approach in accurately detecting sentiments in student comments across different languages, including English, Arabic, and colloquial Arabic.

The rest of this paper is organized as follows: Section 2 gives an overview and a literature review of sentiment analysis in the educational domain. Then, Section 3 describes the steps and data analytic components of the proposed sentiment analysis of student comments on the Twitter platform whereas Section 4 gives the empirical experiments that were performed to show the effectiveness of the proposed approach. Finally, Section 5 gives concluding remarks and future direction to improve this work.

2. Sentiment analysis in the educational domain

2.1. Sentiments analysis

Sentiment analysis is an automatic processing of textual data that automatically detects the emotional tone expressed in texts such as positiveness, negativeness, sadness, happiness, etc. Automatic sentiment analysis has been applied in several domains such as e-commerce, politics, and sports. For instance, in e-commerce, sentiment analysis has enabled companies to gain insights into customer satisfaction levels, and marketing strategies based on the sentiment analysis of customer reviews and feedback. Another example can be cited from politics where sentiment analysis is applied to understand voter sentiment by automatically assessing positiveness towards candidates, policies, political campaigns, etc.

Independently of the specificity of each domain, the conventional sentiment analysis process is usually based on text analytic techniques and typically involves four steps: Text Pre-processing step, Tokeneziation and feature extraction step, Sentiment classification step, and Sentiment interpretations as described in Figure 1.

In the first step, text pre-processing, textual data are collected, cleaned, and pre-processed to remove any irrelevant information, such as special characters, punctuation, and stop-words. Then, in the Tokenization step, the text is divided into smaller units called tokens (i.e. words, phrases, or even sentences). Tokenization enables the breaking down of large textual data into meaningful units ready to be analyzed. Once tokens are prepared, the most relevant features are extracted from the tokens to better represent the studied text. These features can include words, n-grams, parts of speech, or any other syntactic patterns. The choice of selected and relevant features depends on the specific sentiment analysis technique being used. Once the text is represented by features, a classification model is applied to assign sentiment labels to the text. Various sentiment analysis approaches can be used to determine the sentiment orientation of textual units including lexicons-based, corpus-based, machine learning, and deep learning approaches. The final step, sentiment interpretations, aims to interpret the sentiment scores or categories that range from a binary sentiment classification (positive or negative) to a more fine-grained sentiment analysis that includes several categories or sentiment intensity scores.

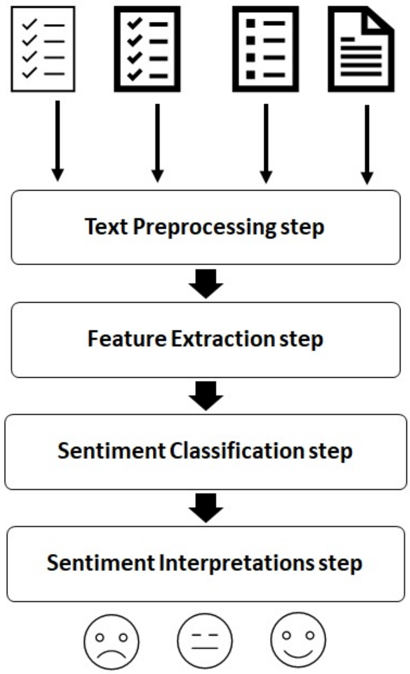

Figure 1. Four steps of the sentiment analysis process: text pre-processing, feature extraction, sentiment classification, sentiment interpretations

2.2. Literature review of sentiment analysis techniques in the educational domain

In the educational domain, sentiment analysis has gained significant attention as it allows an automatic analysis of student feedback on various educational resources such as course contents, teaching experiences, and instructor abilities. Several approaches have been adopted to perform such automatic sentiment analysis within the educational domain. Existing approaches can be classified into three categorie: rule-based, machine learning, and hybrid approaches. Rule-based approaches utilize predefined sets of sentiment words and linguistic rules to classify sentiment polarity. On the other hand, machine learning techniques involve training classifiers on labeled datasets to automatically recognize sentiment patterns. Hybrid models leverage the strengths of both approaches for improved accuracy and flexibility.

Rule-based approaches can be based on a single lexicon or on a whole corpus. The first, lexicon-based, relies on sentiment lexicons or dictionaries that contain words or phrases with pre-assigned sentiment polarity, (i.e. positive, negative, and neutral). Sentiment scores are assigned to text based on the frequency of sentiment words in the lexicon. The lexicon-based approach has been used to label educational data without a need for an excessive manual labeling step. In [31] the authors evaluated the impact of two active learning methods, flipped classrooms and lightweight teams, on student emotions by using a lexicon-based sentiment analysis approach. The authors utilized the National Research Council (NRC) lexicon to assign fine-grained emotions including joy, fear, trust, anger, sadness, disgust, and anticipation. The study was based on both quantitative and qualitative student feedback. Quantitative feedback was measured through Likert scales whereas qualitative feedback was determined through student feelings and opinions about the course. The results indicate that the implementation of these active learning methods is associated with increased positivity in student emotions. Some work [5, 25] tried to improve lexicon-based sentiment analysis in the educational domain either by using open textual feedback or by proposing customized sentiment lexicons for the educational domain. Rajput et al. used open-ended student feedback to evaluate teachers. Textual student feedback was analyzed by employing various text-analytic techniques to build a sentiment analysis-based metric to determine the teacher score. This technique allowed a deeper evaluation of teachers' performance. in another lexicon-based approach, Chauhan et al. [5] proposed to improve the existing Bing lexicon and developed a customized sentiment lexicon. They applied the proposed customized sentiment lexicon to calculate sentiment polarity from academic course feedback texts. The process involved tokenizing sentences using the bag-of-words model and determining the polarity score of each word using both Bing and a new customized lexicon. The authors showed that combining the two lexicons effectively improves both the detection of opinion words and the polarity scoring process. In fact, the quality of the lexicon-based approach is highly relative to the richness of the used dictionary. For this reason, a corpus-based approach can be adopted to enhance sentiment lexicons by incorporating prior information about words and their semantic orientation. The corpus-based approach estimates the semantic polarity of the target word by calculating the semantic distance between a word and a set of positive or negative words.

The second category of sentiment analysis approaches is based on supervised and unsupervised annotation techniques to automatically classify or predict the sentiment orientation of textual data. Several machine learning methods have been used to analyze textual student feedback. In the work of [24] student feedback was analyzed to assess course materials. The authors used the logistic regression technique to classify textual evaluations of course materials into positive, negative, or neutral. In [32] the authors propose a support-vector-machine-based learning model for the early identification of students who are likely to fail in an academic course. The proposed model gives educators the opportunity to early detect academic failure and support students to become self-regulated learners. Other machine learning techniques were also used to automatically detect sentiment orientation including multinomial logistic regression, decision tree, multi-layer perceptron, XGBoost, Gaussian Naive Bayes, and k-nearest neighbors [1, 7, 11, 15, 28]. In order to improve the accuracy of machine learning-based approaches, deep learning techniques, especially Recurrent Neural Networks (RNNs) and Convolutional Neural Networks (CNNs) have been evaluated for sentiment analysis of student feedback. These deep learning models were trained on large textual student feedback to learn the sentiment patterns. In the works of [30], the CNN model was used to evaluate teachers' effectiveness based on student feedback collected through a questionnaire including both structured and unstructured data. In the works of [26], the authors evaluated the ability of RNN to effectively detect the right word emotion based on an ensemble Long Short-Term Memory (LSTM) with attention layers. The authors showed that the use of multiple layers largely improves the result compared with conventional machine learning techniques. Other works also proposed the fusion of several deep learning models. In [3], the authors combined CNN and Bi-LSTM models to detect users' feelings. The authors showed that the fusion of CNN and BiLSTM improves sentiment detection accuracy compared with conventional machine learning techniques. In fact, all the deep learning models, including RNN, CNN and LSTM, have shown effectiveness in capturing the sequential dependencies in textual data and capturing local patterns and features in educational comments, feedback, and texts. However, these deep learning-based approaches have shown their limits in detecting contextual nuances and semantic relationships of texts.

More recent learning-based models [8,17,22,29] tried to solve the issue of contextual nuances by using pre-trained transformer models, such as Bi-directional Encoder Representations from Transformers (BERT) and Generative Pre-trained Transformer (GPT). In [8], the authors uses the BERT model to handle the complex relationships between students, teachers, and courses, as well as to tackle various challenges encountered during the learning process. The authors demonstrated the effectiveness of BERT in enhancing the analysis of student data. Similarly, in [17], the authors combine deep learning techniques with BERT to accurately detect sentiment polarity from collected comments. Their proposed model, BERT-CNN, outperforms traditional machine learning models, showcasing the power of BERT in sentiment analysis of student data. Moreover, the authors in [18] and [22] explored the use of BERT for improved contextual sentiment analysis of textual data. These studies demonstrated the effectiveness of BERT in capturing nuanced sentiment information in the context of student feedback. In addition to BERT, recent research has explored the effectiveness of GPT-based models in sentiment analysis of student feedback. In [23] and [3], the authors investigated the sentiment classification capabilities of various GPT-based models, including prompt-based and fine-tuning GPT models. The results demonstrated the superior predictive performance of GPT approaches, along with their ability to understand contextual information and detect sarcasm. This highlights the potential of GPT-based models in capturing nuanced sentiment information in the analysis of student feedback. Furthermore, a comparative study conducted by [22] further supports the effectiveness of GPT-based models in understanding and interpreting student sentiments in diverse research scenarios. In fact, Both BERT and GPT-based models have proven to be powerful tools for sentiment analysis in the context of education. They offer the advantage of leveraging pre-training on large-scale datasets, enabling them to capture contextual information and nuances in sentiment expression without the need for extensive feature engineering [10].

The third category of sentiment analysis approaches in the educational domain combines both lexicon-based and learning-based methods to leverage the strengths of each method. In [27], the authors proposed a deep learning-based opinion mining system based on a two-layered Long Short-Term Memory model: aspect extraction and sentiment polarity detection layers. The first layer predicts the aspects of student feedback while the second specifies the orientation (positive, negative, and neutral). The system is enforced using a domain embedding dictionary in both layers. Also, the authors in [2] proposed to use BERT, TextBlob, machine learning, and ensemble methods for an improved user feedback analysis. BERT and TextBlob were used for text annotations while machine learning and ensemble methods were used for sentiment classification.

Similarly in [21] and [14], the authors combined machine learning and lexicon-based approaches for sentiment analysis of students' feedback. Textual feedback was trained using a TF-IDF representation enhanced with contextual lexicon-based features. The authors showed that the combination of both approaches effectively improves results compared to conventional techniques. However, combining both approaches may be computationally expensive while requiring additional prepossessing steps, feature engineering, and model integration. Despite these limits, hybrid sentiment analysis can offer advantages by leveraging the strengths of both lexicon-based and machine learning-based approaches. A hybrid approach can provide a deeper understanding of sentiment by combining explicit and implicit rule-based heuristics.

2.3. Challenges of implementing automatic sentiment analysis in the educational domain

The automatic sentiment analysis of student comments on social networks faces several challenges that need to be addressed to effectively analyze and determine the emotional tone expressed in textual data. First, the unstructured nature of textual data makes automatic analysis of these data highly difficult and requires a pre-processing step to transform the data into a numerical format that can be easily used as inputs for automatic sentiment analysis algorithms. This task includes word extractions, removing punctuation, converting to lowercase, handling special characters, and many other text pre-processing tasks. All these tasks would be more difficult to perform on student feedback collected from social platforms given that students often use informal language, slang, abbreviations, and emojis in their social media comments. These linguistic elements add complexity to sentiment analysis as they may have connotations specific to social platforms and student interactions. It would be challenging to perform automatic sentiment analysis algorithms on such data types.

Another challenge is the ambiguity in natural languages. In fact, words can have multiple meanings depending on the context in which they are used. This ambiguity makes it difficult to accurately determine the sentiment expressed in a particular text. Contextual understanding and disambiguation techniques are necessary to overcome this challenge. Additionally, student comments on social networks may express subjective opinions and thoughts that do not clearly indicate positiveness or negativeness. Developing robust systems that can effectively capture and quantify subjective student comments is of high importance to effectively identify the right expressed sentiments. To deal with all these challenges, we propose in the next section a contextual aware sentiment analysis system that can effectively solve all the discussed problems.

3. Proposed approach

We propose in this section a new ChatGPT-based approach for the sentiment analysis of student comments in social networks. The proposed approach, referred to as Twitter Sentiment Analysis of Student Comments (TSASC), aims to automatically detect the polarity of student comments on the Twitter social platform.

TSASC combines the advantages of lexicon-based and transformer-based methods in order to build the sentiment polarity of student comments. Sentiment polarity scores are built using both TextBlob and ChatGPT through a three-phase approach as described in Figure 2. We describe in the following the different three phases and the different tasks for each phase.

3.1. Phase 1: Twitter student comments cleaning

The first phase aims to build a relevant and clean textual database of student comments. By using "Tweepy", we collected more than 5000 comments from Twitter pages related to five Saudi high educational institutions. Most of the collected comments are in Arabic and colloquial Arabic. Only a few comments are written in English. Given that many comments contain advertisements or request academic or non-academic information and are not relevant to the sentiment analysis task, we removed all the comments containing an advertisement, containing a question mark, or written in a question form. After that, by using the "re" library, we tried to clean the student comments by removing all mentioned URLs, users, tags, dates, and numbers.

We also removed special characters, punctuation, and symbols that do not contribute in detecting the sentiment polarity. We also converted all comments to lowercase to ensure consistency and avoid case differences for English comments. However, concerning emoticons and emojis, by using the "Emojis" library, we defined a list of positive and negative emoticons and then replaced all these emoticons with the words "positive" or "negative" for English comments and with the words "ijabi" and "salbi" for Arabic and colloquial Arabic to refer to positiveness and negativeness in each comment. The other non-defined emoticons and emojis are deleted from student comments.

Figure 3 shows an example of Twitter emoticons that were used in student comments and were replaced by positive and negative words in English, Arabic, and colloquial Arabic.

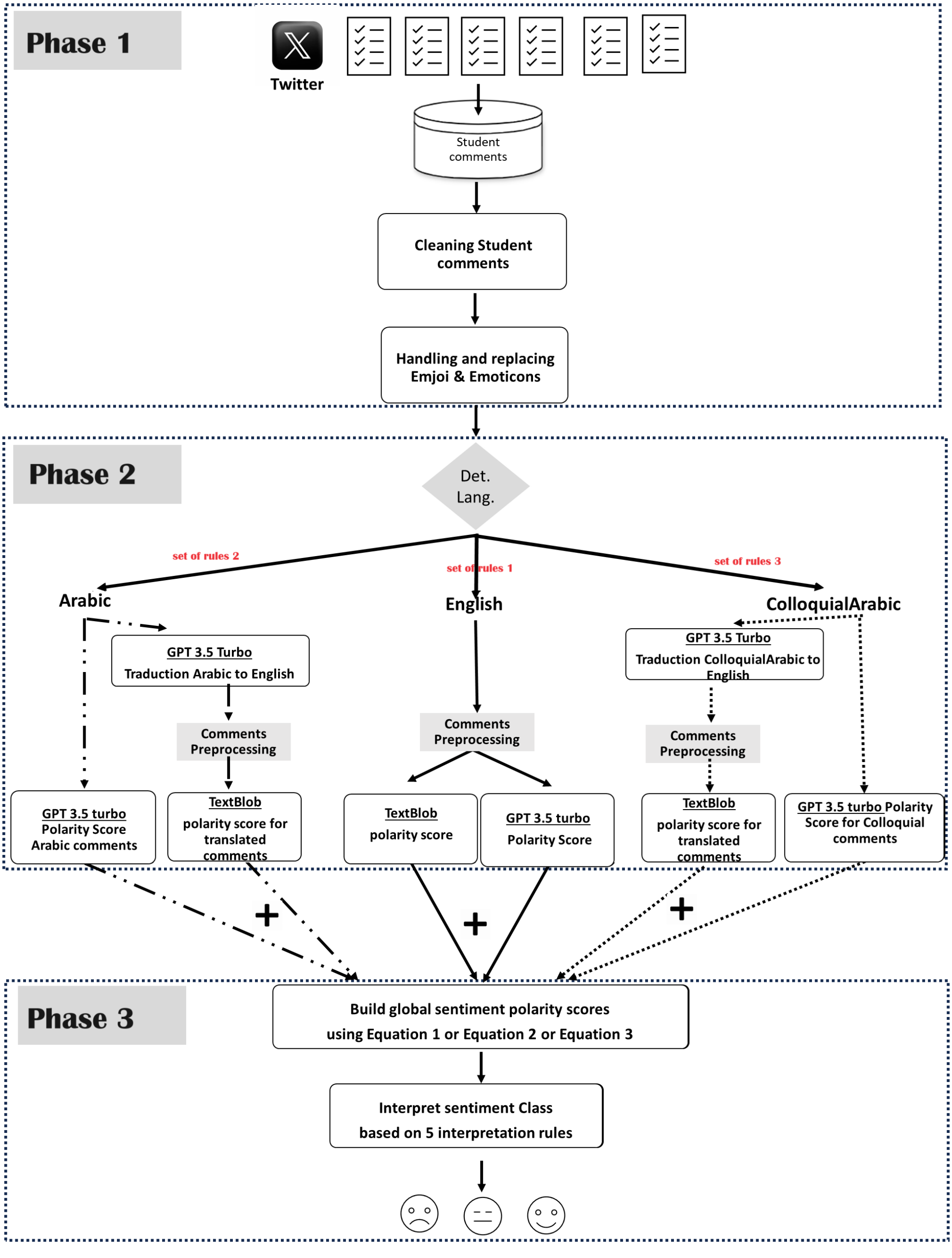

Figure 2. Proposed hybrid sentiment analysis of student comments in social platforms. Sentiment polarity scores are built using both TextBlob, as a lexicon-based method, and ChatGPT as a transformer-based method

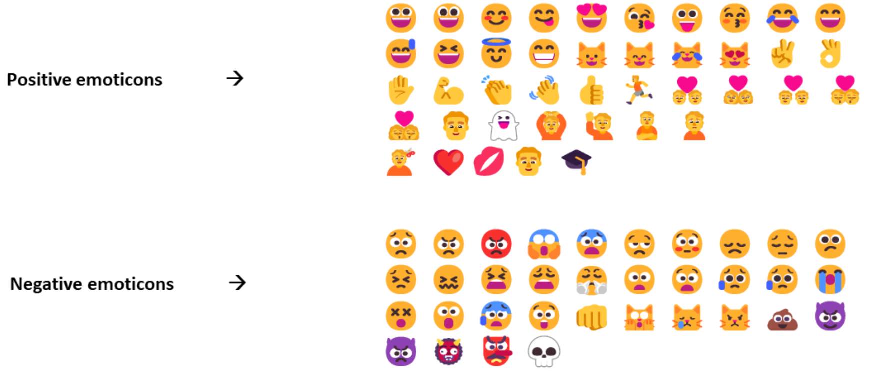

Figure 3. Examples of positive and negative Twitter emoticons. All positive emoticons are replaced by the words "positive" while negative emoticons are replaced by the words "negative"

3.2. Phase 2: building sentiment polarity and subjectivity scores

The second phase aims to build sentiment polarity and subjectivity scores of student comments using TextBlob and ChatGPT. The first, TextBlob, is a Python Natural Language Processing (NLP) library that provides simple and various NLP operations and functionalities including part-of-speech tagging, tokenization, spell-checking and sentiment analysis. It facilitates common NLP tasks and provides for developers with a convenient interface to analyze and process the textual data. The sentiment analysis function in TextBlob begins by the creation of an object by passing the text to be analyzed as a parameter. Then, the text is tokenized into a bag of words for further analysis. After that, the polarity score is calculated for each single word in the text using a sentiment lexicon (pre-defined dictionary). TextBlob utilizes its built-in sentiment lexicon using a pre-defined collection of words with associated sentiment scores. After assigning individual scores to all the words, the global sentiment for the input text is calculated by a pooling operation like taking an average of all single sentiment scores. The sentiment polarity score is normalized to a value between -1 and 1 where -1 indicates highly negative sentiment, 1 indicates highly positive sentiment, and 0 for neutral sentiment. TextBlob allows also building a subjectivity score for each comment that represents the degree of subjectivity or objectivity in a given text. The score is a numeric value between 0 and 1 where 0 indicates highly objective text and 1 indicates highly subjective. A subjectivity score close to 1 indicates that the comment may contain personal opinions or express an emotion. Figure A1 gives a small example of building sentiment polarity and subjectivity scores for the input text *"I absolutely love the teacher methodology! It's amazing!"*. TextBlob builds a positive sentiment polarity equal to 0.6875 and also a high subjectivity for the input text equal to 0.75.

The second tool used for building sentiment polarity scores is ChatGPT [33] which allows the generation of human-like responses based on a given user request, also called a user prompt. This tool has been trained on diverse huge textual data and supports several human languages including several colloquial languages. We explored the ChatGPT natural language processing capabilities by using the recently proposed OpenAI API and based on GPT-3.5-turbo learning model. The OpenAI GPT-3.5-turbo learning model has been trained to understand human natural language and allows to provide text outputs in response to a user prompt. The design of a user prompt is similar to designing instructions in a computer program describing how to successfully complete a task. Several tasks can be defined including text analyzer, question answer about a knowledge base, translating text, or interpreting the sentiments in a given text.

To build sentiment polarity and subjectivity scores for a given input text using the GPT-3.5-turbo model through the OpenAI API, we designed two functions, "analyze-sentiment-polarity" and "analyze-subjectivity", and requested the "Chat Completions API" to build responses containing the calculated scores. We give in the following a description of the two designed functions:

```
def analyze_sentiment_polarity(sentence):
    response = client.chat.completions.create(
      model="gpt-3.5-turbo",
      messages=[
        {
          "role": "system",
          "content": "You will be provided with a given textual
          ↪  sentence in the context of education, and your task is
          ↪  to calculate a sentiment score between -1 and 1."

        },
        {
          "role": "user",
          "content": sentence
        }
      ],
      temperature=0.2,
      max_tokens=10,
      top_p=1
    )

    sentiment_score = response.choices[0].message.content
    return sentiment_score


```

```
def analyze_subjectivity(sentence):
    response = client.chat.completions.create(
      model="gpt-3.5-turbo",
      messages=[
        {
          "role": "system",
          "content": "You will be provided with a given textual sentence in the context of education, and your task is to calculate a subjectivity score between 0 and 1"
        },
        {
          "role": "user",
          "content": sentence
        }
      ],
      temperature=0.2,
      max_tokens=10,
      top_p=1
    )

    subjectivity_score = response.choices[0].message.content

    return subjectivity_score
```

For the first function, "analyze-sentiment-polarity," we utilize the OpenAI *client.chat.completions.create()* function with various parameters. We start by specifying the GPT-3.5-turbo model as our learning model. In the design of the message parameter, we define the system and user roles. In the system's role, we request the model to generate a sentiment score between -1 and 1, representing the sentiment polarity of a given input textual sentence. We explicitly mention the context by using the term "education" to provide contextual information. By incorporating the intended context, the fine-tuned GPT-3.5-turbo model can generate more accurate sentiment scores that are contextually aware. Regarding the user's role, we indicate that the user will provide an input textual sentence for sentiment analysis. Additionally, we set the *temperature* parameter to a low value of 0.2 to ensure more deterministic and stable sentiment scores. The *max_token* parameter is set to 10, allowing us to effectively receive and store the score results. Finally, we set $top\_p = 1$, which considers all possible tokens without the need for sampling. These same parameters are also applied to the second function, "analyze-subjectivity", which we designed to calculate a subjectivity score using the GPT-3.5-turbo model. In this case, the system role is responsible for generating a subjectivity score between 0 and 1 with an wxlocit indication of the "education" context. For a complete description and call of the defined functions through the OpenAI API please refer to Appendix 2.

To provide readers with a clearer understanding of the sentiment polarity and subjectivity scores obtained using TextBlob and ChatGPT, Table 1 presents the results for different sample English messages. These scores were generated using TextBlob and ChatGPT tools and reveal variations in sentiment and subjectivity assessments. We show that TextBlob tends to assign slightly lower sentiment scores compared to ChatGPT. This difference suggests that TextBlob may be more conservative in its sentiment analysis, potentially leading to a more neutral sentiment classification for some messages. On the other hand, ChatGPT often exhibits lower subjectivity scores, indicating a more objective interpretation of the given statements. It is also important to note that the reported results are specific to the English language given that TextBlob is limited to English comments and cannot be applied to Arabic or colloquial Arabic comments.

Table 1
Sentiment analysis results

#	Message	TextBlob	ChatGPT
1	"the teacher gives a good textbook for the operating system course"	sentiment = 0.7 subjectivity = 0.6	sentiment = 0.7 subjectivity = 0.3
2	"I'm not sure how I feel about exams"	sentiment = –0.25 subjectivity = 0.88	sentiment = –0.4 subjectivity = 0.7
3	"Do you get nervous before an exam?"	sentiment = 0 subjectivity = 0	sentiment = –0.3 subjectivity = 0.7
4	"This was a helpful example but I would prefer another one"	sentiment = 0 subjectivity = 0	sentiment = 0.2 subjectivity = 0.8
5	"I absolutely love the teacher methodology! It's amazing!"	sentiment = 0.68 subjectivity = 0.75	sentiment = 0.9 subjectivity = 0.1

To leverage the strengths of both tools and create a more effective sentiment analysis score, we propose to combine scores from TextBlob and ChatGPT to take advantage of the nuanced analysis provided by each tool. Respecting to the comment detected language, polarity and subjectivity scores of student comments are calculated based on a set of rules and tasks as described in the second phase of Figure 2. We give in the following a detailed description of these tasks and rules:

- **Set of rules 1** (detected language is English). A pre-processing of English comments is performed by removing stop words that do not contribute in determining the sentiment polarity such as "from", "this", "on", "was", etc. We used a list of English stop words available in the Python Natural Language Toolkit [4]. Then, a stemming task is performed to reduce words in each comment to their root forms. This can help in consolidating similar words and reducing vocabulary size when using TextBlob. After that, the pre-processed comments are used as inputs for both TextBlob and ChatGPT. For each comment EN_i, we generated four scores: $P_{Blob}(EN_i)$ and $S_{Blob}(EN_i)$ that represents sentiment polarity and subjectivity scores calculated using TextBlob and $P_{GPT}(EN_i)$ and $S_{GPT}(EN_i)$ that represents sentiment polarity and subjectivity score calculated using ChatGPT 3.5 turbo. For ChatGPT, we added a contextual indication "education" in the textual request of building a sentiment score between −1 and 1 and also in detecting the sentiment subjectivity of the whole comment. The contextual indication allows the pre-trained ChatGPT model to give a more accurate sentiment analysis of student comments.

- **Set of rules 2** (detected language is Arabic). Concerning sentiment scores built by ChatGPT, Arabic comments are given as inputs without any text pre-processing tasks. ChatGPT is pre-trained to analyze such data and build an effective sentiment polarity score. However, a contextual indication "م" that refers to education is added to improve the contextual analysis when building the sentiment polarity $P_{GPT}(AR_i)$ and the subjectivity $S_{GPT}(AR_i)$ scores. On the other hand, to build sentiment scores using TextBlob, we translated Arabic comments to English using ChatGPT, then pre-processed the output text by removing stop words and finally the sentiment polarity $P_{Blob}(AR_i)$ and the subjectivity scores $S_{Blob}(AR_i)$ are built using TextBlob sentiment function.
- **Set of rules 3** (detected language is colloquial Arabic). Similarly to Arabic comments, colloquial Arabic comments are given as inputs to ChatGPT without a pre-processing task. Only a contextual indication "م" is added to the ChatGPT request to refer to comments relative to the education domain for building the sentiment polarity $P_{GPT}(CA_i)$ and the subjectivity $S_{GPT}(CA_i)$ scores. However, colloquial Arabic comments are translated to English using ChatGPT and then pre-processed by removing stop words and given as inputs to TextBlob to generate the sentiment polarity $P_{Blob}(CA_i)$ and the subjectivity $S_{Blob}(CA_i)$ scores.

3.3. Phase 3: building global sentiment polarity score and interpreting sentiment classes

This phase aims to assign a sentiment class for each student comment based on polarity scores built in the previous step. In the first step, building global sentiment polarity scores, a global sentiment score is calculated for each student comment based on a combination of polarity scores obtained using TextBlob and ChatGPT. To build a global score for each comment EN_i, $AR_i$and CA_i, we defined a combination function that uses the subjectivity scores as weights for calculating global sentiment polarity scores in the overall function as follows:

- **English comments**: for each English comment EN_i, given the two sentiment polarity scores $P_{Blob}(EN_i)$ and $P_{GPT}(EN_i)$ and the two subjectivity scores $S_{Blob}(EN_i)$ and $S_{GPT}(EN_i)$ built using TextBlob and ChatGPT, the global sentiment score $P(EN_i)$ is calculated by:

$$P(EN_i) = \frac{(S_{GPT}(EN_i) \cdot P_{GPT}(EN_i)) + (S_{Blob}(EN_i) \cdot P_{Blob}(EN_i))}{S_{GPT}(EN_i) + S_{Blob}(EN_i)} \quad (1)$$

- **Arabic comments**: for each arabic comment AR_i, given the two sentiment polarity scores $P_{Blob}(AR_i)$ and $P_{GPT}(AR_i)$ and the two subjectivity scores $S_{Blob}(AR_i)$ and $S_{GPT}(AR_i)$ calculated using TextBlob and ChatGPT, the global sentiment score for each arabic comment AR_i is calculated by:

$$P(AR_i) = \frac{(S_{GPT}(AR_i) \cdot P_{GPT}(AR_i) + S_{Blob}(AR_i) \cdot P_{Blob}(AR_i))}{S_{GPT}(AR_i) + S_{Blob}(AR_i)} \tag{2}$$

- **Colloquial Arabic comments**: for each colloquial arabic comment CA_i, given the two sentiment polarity scores $P_{Blob}(CA_i)$ and $P_{GPT}(CA_i)$ and the two subjectivity scores $S_{Blob}(CA_i)$ and $S_{GPT}(CA_i)$ calculated using TextBlob and ChatGPT, the global sentiment score for each colloquial arabic comment $P(CA_i)$ is calculated by:

$$P(CA_i) = \frac{(S_{GPT}(CA_i) \cdot P_{GPT}(CA_i) + S_{Blob}(CA_i) \cdot P_{Blob}(CA_i))}{S_{GPT}(CA_i) + S_{Blob}(CA_i)} \tag{3}$$

We notice in Equation (1), (2) and (3) that a bigger weight is assigned for ChatGPT scores compared to those built using TextBlob. This choice is based on our study of small examples of comments that showed better performance of ChatGPT compared to TextBlob specifically for Arabic and colloquial Arabic comments. One can adjust these weights by assigning similar weights or giving more importance to any selected tool.

Once global polarity scores for student comments are calculated, the next step aims to interpret the sentiment classes based on the following defined five interpretation rules:

1. **Interpretation rule 1** (*if the global polarity score is above a threshold* 0.2). Classify the comment as positive.
2. **Interpretation rule 2** (*if the global polarity score is under a threshold of* -0.2). Classify the comment as negative.
3. **Interpretation rule 3** (*if the global polarity score of a comment is in the interval* $[-0.2, -0.1]$). If the calculated subjectivity of TextBlob (S_{Blob}) and ChatGPT (S_{GPT}) are both above -0.2 and both calculated polarities are negative then classify the comment as negative else classify the comment as neutral.
4. **Interpretation rule 4** (*if the global polarity score of a comment is in the interval* $[0.1, 0.2]$). If calculated subjectivity of TextBlob (S_{Blob}) and ChatGPT (S_{Blob}) are both above 0.2 and both calculated polarities for the comment are positive then classify the comment as positive else classify the comment as neutral.
5. **Interpretation rule 5** (*if the global polarity score is in the interval* $[-0.1, 0.1]$ *(within a range around* 0*)*). Classify the comment as neutral.

We considered for all these rules a subjectivity threshold equal to 0.2 and a polarity threshold equal to 0.1. These thresholds are fixed based on an experimental study of subjectivity and polarity scores built for all the comments. One can adjust these thresholds based on the specificity of the application or the specificity of the studied data.

4. Experiments and empirical evaluations

4.1. Data set description

In order to evaluate the quality of the proposed sentiment analysis approach, we manually annotated an ensemble of 1266 student comments that were extracted from Twitter pages of five Saudi higher colleges on the Twitter platform posted between April 2022 and June 2023. The annotated dataset contains 1266 comments including 134 in English, 460 in Arabic and 672 in colloquial Arabic. The selected comments were tagged by a human annotator with sentiment labels including positive, negative, and neutral categories for each language. The statistics for annotated comments are described in Table 2. The final distribution of the sentiment labels in the overall dataset is as follows: 607 are labeled as neutral, 355 are labeled as positive, and 304 are labeled as negative.

Table 2

Statistics of the build dataset from five university pages on the Twitter platform

Dataset	Language	Classes
Twitter student comments dataset (1266)	English (134)	Positive (39) Negative (48) Neutral (47)
	Arabic (460)	Positive (108) Negative (117) Neutral (235)
	Colloquial Arabic (672)	Positive (188) Negative (139) Neutral (325)

As described in Section 3.1, several pre-processing steps were applied to enhance the quality of the extracted textual comments. Irrelevant comments including advertisements were filtered out. English comments were transformed into lowercase, tokenized, and split into individual words. Also, stop words, punctuation marks, and special characters were removed. The resulting pre-processed dataset is used as input for the sentiment classification methods.

To better explore the built student comments dataset, we visualized the word cloud of English, Arabic, and colloquial Arabic comments. The word clouds provide an overview of the keywords and topics discussed by students giving insights into their sentiments, concerns, and experiences related to education and university life. Word clouds are generated by analyzing the frequency of words in the comments and representing them graphically such that the size of each word indicates its relative occurrence. The most frequently used words appear larger and bolder while less frequent words are visualized smaller. For English comments, we colored positive and negative words in green and red based on the TextBlob dictionary. The coloring cannot be performed for Arabic and colloquial Arabic given that TextBlob only gives polarity of English terms. Figure 4 shows the most used English terms in the built dataset including “course”, “teacher”, “instructor”, “material”, etc. This figure also shows a few detected positive words (i.e. “easy”, “much” and “challenging”) and a few detected negative words (i.e. “unfair”, “difficult” and “minimal”). We notice that all the colored terms have been well classified whether for positive or negative polarities.

Figure 4. Wordcloud of extracted student comments in English. Positive and negative words are schematized in green and red colors based on the TextBlob dictionary

Although the high precision of classifying positive and negative terms, Figure 4 shows the limit of using TextBlob for polarity detection since several positive and negative words are not detected. For example, evident words that express positiveness such as “timely” and “motivated” and also words that express negativeness such as “inaccessible”, “unsupported” and “disinterested” are not detected and classified by TextBlob. This shows the limit of using lexicon-based algorithms, based on TextBlob dictionary, for detecting the sentiment polarity of student comments. Concerning Arabic and colloquial Arabic comments, Figure 5 and Figure 6 show the most frequent Arabic and colloquial Arabic words. By examining the prominent words in the two figures, we notice the existence of several Arabic words expressing positiveness and negativeness related to the educational field such as م and “ و ” that refer to “professor” and “training” respectively. These two figures also show the effectiveness of ChatGPT in separating Arabic from colloquial Arabic comments. Figure 6 visualizes several words from the Arabic colloquial language such as “bidina = أ” and “ yji = آ” as are pronounced in Arabic to refer to “we can do something” and “possible”.

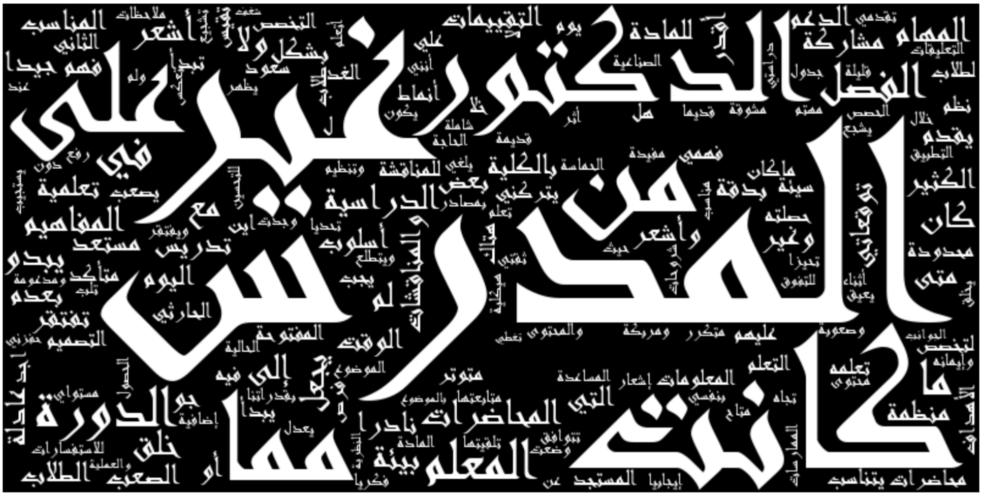

Figure 5. Wordcloud of extracted student comments in Arabic

Figure 6. Wordcloud of extracted student comments in colloquial Arabic

4.2. Experimental results and discussions

In order to evaluate the performance of the proposed approach compared with existing methods, we used four evaluation measures: *Precision*, *Accuracy*, *Recall*, and *F1-score*. These measures are used to evaluate whether the predictions of sentiment classes are correct with respect to the underlying correct sentiment labels.

Precision measures the proportion of correctly predicted comments for a specific sentiment class over the total comments predicted as that class, and is calculated using the formula:

$$Precision = \frac{TP}{TP + FP} \tag{4}$$

where TP denotes true positives (correctly predicted instances) and FP represents false positives (incorrectly predicted instances). Accuracy evaluates the overall correctness of sentiment class predictions across all classes, and is defined as:

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN} \tag{5}$$

where TN denotes true negatives (correctly predicted instances of sentiment classes other than the evaluated class) and FN represents false negatives (incorrectly predicted instances of the evaluated class). Concerning the Recall measure, it evaluates the proportion of correctly predicted instances of a specific sentiment class over the total comments that belong to that class, and is calculated by:

$$Recall = \frac{TP}{TP + FN} \tag{6}$$

Finally, *F1-score* combines precision and recall to provide a single metric that balances both measures, and is computed using the formula:

$$F1\text{-}score = \frac{2 \cdot Precision \cdot Recall}{Precision + Recall} \tag{7}$$

All these evaluation measures are computed individually for each sentiment class (positive, negative, neutral), and then an overall weighted score is generated for the entire dataset, considering the importance of each sentiment class.

We compared the effectiveness of the proposed sentiment analysis approach with several existing methods including lexicon-based, machine learning, deep learning, and transformer-based methods. Concerning machine learning methods, we evaluated the effectiveness of four machine learning methods which are Random Forest (RF), Support Vector Machine (SVM) using both linear and polynomial kernels and K-Nearest Neighbors (KNN). For all machine learning methods, features are extracted using the bag-of-words model while frequencies are calculated by using the Term Frequency-Inverse Document matrix (TF-IDF) technique. Evaluation measures are built by calculating the average of five-fold cross-validation. For each loop, a split of data into training and testing, with sizes 60% and 40%, is performed. Concerning deep learning methods, we evaluated two recurrent neural network methods which are LSTM (Long Short-Term Memory) and GRU (Gated Recurrent Unit). Finally, for transformer-based methods, we assessed the performance of both BERT_{base} and RoBERTa which is an optimized version of the BERT pre-trained model.

Table 3 presents obtained performance measures including *Accuracy* (Acc.), *Precision* (Prec.), *Recall* (Rec.), and *F1-score* (F1) for each sentiment class (Positive, Negative, and Neutral), as well as an overall average over the three classes computed for each evaluation measure. This table shows that the proposed approach, TSASC, achieved the highest overall scores evaluated by 0.81, 0.86, 0.82 and 0.85 for accuracy, precision, recall, and F1-score respectively. All these obtained scores largely exceed all the other built scores in Table 3. For the machine learning category, we show that all evaluated methods do not exceed an overall F1-score of 0.43 indicating the low sentiment analysis performance of machine learning methods in identifying the true sentiment classes of student comments. We show that SVM method with a linear kernel gives the lowest result in predicting the sentiment of student comments with an overall accuracy of 36% while RF method showed a slight improvement compared to the other machine learning methods with an overall accuracy of 0.45%. For the deep learning category, we show that RNN with a Long Short-Term Memory (LSTM) architecture achieves an overall F1-score of 0.56, while RNN with a Gated Recurrent Unit (GRU) architecture achieves an overall F1-score of 0.59. These results indicate that deep learning models, based on both LSTM and GRU architectures, outperform the machine learning methods in detecting sentiment classes of student comments. In the Lexicon-based approaches, both TextBlob and Vader achieve nearly similar overall performances of around 0.65. This suggests that these lexicon-based methods performed better than both machine learning and deep learning approaches. Although the dictionary of TextBlob and Vader does not include an exhaustive list of words with positive and negative polarities, the lexicon-based approach has achieved better performance compared to machine learning and deep learning approaches in detecting sentiment classes of student comments. Similarly, transformer-based methods, including BERT_{base} and RoBERTa have shown good results compared to machine and deep learning approaches. For instance, the overall F1 scores attained by BERT*base* and RoBERTa were 0.71 and 0.75 respectively. Nevertheless, these two methods have demonstrated limitations in accurately detecting neutral student comments. Specifically, the RoBERTa method obtained a precision, recall, and F1 score of 0.52, 0.55, and 0.52 respectively.

Table 3

Comparison of the effectiveness of the proposed TSASC approach compared to conventional sentiment analysis methods

	Method	Class	Performance measures			
			Acc.	Prec.	Rec.	F1
Lexicon-based	TextBlob	Positive	0.65	0.70	0.62	0.65
		Negative	0.64	0.68	0.61	0.63
		Neutral	0.76	0.79	0.73	0.75
		Overall	0.70	0.73	0.69	0.71
	Vader	Positive	0.65	0.70	0.62	0.64
		Negative	0.64	0.71	0.61	0.63
		Neutral	0.66	0.69	0.63	0.65
		Overall	0.65	0.70	0.62	0.64

Table 3 cont.

	Method	Class	Performance measures			
			Acc.	Prec.	Rec.	F1
Machine learning	RF	Positive	0.45	0.48	0.42	0.44
		Negative	0.44	0.49	0.41	0.43
		Neutral	0.46	0.47	0.43	0.44
		Overall	0.45	0.47	0.42	0.43
	SVM (Linear Kernel)	Positive	0.39	0.31	0.36	0.32
		Negative	0.38	0.32	0.35	0.33
		Neutral	0.40	0.40	0.37	0.38
		Overall	0.39	0.37	0.36	0.36
	SVM (Polynomial Kernel)	Positive	0.41	0.43	0.49	0.45
		Negative	0.40	0.44	0.48	0.45
		Neutral	0.42	0.42	0.40	0.40
		Overall	0.41	0.43	0.42	0.41
	KNN	Positive	0.42	0.45	0.40	0.41
		Negative	0.41	0.46	0.49	0.47
		Neutral	0.43	0.44	0.41	0.42
		Overall	0.42	0.44	0.43	0.43
Deep learning	RNN (LSTM)	Positive	0.55	0.58	0.52	0.54
		Negative	0.54	0.59	0.53	0.55
		Neutral	0.56	0.57	0.53	0.54
		Overall	0.56	0.58	0.52	0,54
	RNN (GRU)	Positive	0.59	0.51	0.56	0.54
		Negative	0.58	0.52	0.55	0.53
		Neutral	0.60	0.61	0.61	0.61
		Overall	0.59	0.59	0.59	0.59
Transformer-based	$BERT_{base}$	Positive	0.75	0.77	0.71	0.72
		Negative	0.69	0.70	0.76	0.72
		Neutral	0.46	0.48	0.49	0.48
		Overall	0.70	0.73	0.69	0.71
Transformer-based	RoBERTa	Positive	0.79	0.78	0.79	0.79
		Negative	0.80	0.81	0.79	0.80
		Neutral	0.51	0.52	0.55	0.52
		Overall	0.72	0.71	0.72	0.75
Proposed approach	**TSASC**	Positive	0.85	0.80	0.82	0.81
		Negative	0.84	0.82	0.91	0.85
		Neutral	0.86	0.89	0.73	0.79
		Overall	0.85	0.86	0.82	0.81

Obtained results in Table 3 show that our TSASC approach has significantly outperformed all other conventional methods including machine learning, deep learning, as well as transformer-based and lexicon-based approaches. This finding shows the effectiveness of the proposed approach in accurately identifying sentiment classes on the student comments dataset and also shows the effectiveness of leveraging ChatGPT capability for sentiment classification. Reported results also show an interesting performance of lexicon-based and transformer based approaches compared to deep learning and machine learning approaches.

In order to effectively evaluate the performance of ChatGPT in giving better contextual-improved sentiment analysis of student comments, we evaluated its effectiveness compared to Google translation. Concerning our approach, rather than directly detecting the sentiment polarity of Arabic and colloquial Arabic comments using ChatGPT, we translated all these comments into English language using Google Translate and then detected sentiment polarity by using TextBlob. Table 4 presents the results of the comparison of ChatGPT and Google Translation and their impacts on the sentiment analysis of student comments by using machine learning, deep learning, and lexicon-based approaches.

Table 4

Comparison of the impacts of ChatGPT and Google Translator on the sentiment analysis of student comments using machine learning, deep learning, lexicon-based, and the proposed approach. ChatGPT and Google Translator are used as automatic tools to translate Arabic and colloquial Arabic comments into English

	Method	Google Translate		ChatGPT translation service	
		Acc.	F1	Acc.	F1
Lexicon-based	TextBlob	0.58	0.59	0.69	0.71
	Vader	0.54	0.56	0.65	0.64
Machine learning	RF	0.37	0.39	0.45	0.43
	SVM (linear kernel)	0.34	0.36	0.39	0.36
	SVM (polynomial kernel)	0.40	0.41	0.41	0.41
	KNN	0.40	0.40	0.42	0.43
Deep learning	RNN(LSTM)	0.55	0.57	0.56	0.58
	RNN(GRU)	0.56	0.57	0.59	0.59
Transformer-based	BERT_{base}	0.65	0.67	0.70	0.71
	RoBERTa	0.69	0.71	0.72	0.75
Proposed approach	TSASC	0.67	0.70	0.85	0.81

The performance of each method is evaluated using an overall score of *Accuracy* (Acc.) and *F1-score* (F1) measures. For the machine learning and deep learning category, we do not show a high impact on obtained results. For example, the Random Forest method achieves an accuracy and *F1-score* of around 0.40 by using ChatGPT and Google translation. In fact, for machine learning and deep learning category, the computational framework does not take into account the semantics of words and only focuses on the similarity of words between student comments to build sentiment classes. This fact explains the nearly same results obtained by ChatGPT and Google Translator for all machine learning and deep learning methods. Furthermore, the effectiveness of transformer-based methods remains consistent across different translation services. For instance, the RoBERTa method demonstrated comparable accuracy and F1 scores by using Google Translate and ChatGPT translation services. When employing Google Translate, the achieved scores were 0.69 and 0.71, while utilizing the ChatGPT translation service yielded scores of 0.72 and 0.75. Despite the superior performance of transformer-based methods compared to machine and deep learning approaches, no discernible impact was observed concerning the choice of translation service on the final results. However, when using a lexicon-based approach, Table 4 shows a high improvement of results by using ChatGPT compared to Google translator for both TextBlob and Vader. For example, when using ChatGPT TextBlob achieves an accuracy of 0.69 and an *F1-score* of 0.71 compared to an accuracy of 0.65 and an *F1-score* of 0.64 when using Google Translator. Furthermore, transformer based methods also show high performance compared to machine In the same way, we show a high improvement when using ChatGPT for our proposed approach. ChatGPT with TSASC achieves an accuracy of 0.85 and an *F1-score* of 0.81 compared to 0.67 and 0.7 by using Google Translate. This obtained result shows the effectiveness of directly detecting sentiment polarity of Arabic and colloquial Arabic comments rather than considering a translating step of the comment into English. This obtained result also confirms the contextual improved capability of the proposed approach compared to other approaches and its ability to detect more accurate sentiment polarity of student comments through using ChatGPT capability.

4.3. Ethical considerations of student sentiment analysis

The sentiment analysis of student data collected from their activities on social networks has gained significant attention leading to the development of various tools, packages, and methods that enable effective and automatic analysis of these data. However, the collection and analysis of such data has lead to crucial ethical considerations that require careful attention. One primary ethical concern is the privacy protection. The collected student data may include personal and sensitive information pertaining to their daily lives. It is crucial that sentiment analysis tools incorporate pre-processing steps to anonymize data and remove any personally identifiable information to prevent potential privacy breaches. It is worth noting that available tools may be limited to accessing only public student information obtained from public university pages.

Another ethical consideration concerns the non-disclosure of student perceptions, experiences, or opinions regarding subjects, courses, or teachers. This information should only be shared with individuals who are responsible for improving the student experience. It is essential to safeguard this information from other parties looking to exploit it for commercial purposes. Individuals involved in such projects may sign a consent form affirming non-disclosure of the results for any commercial use. Furthermore, individuals working on such projects should seek approval from relevant ethics committees or institutional review boards to ensure compliance with ethical guidelines and regulations.

This leads to a more generic ethical consideration that concerns the security of student data. Student data must be protected against unauthorized access, breaches, or misuse. Employing encryption techniques, secure data storage systems, and implementing restricted access controls are essential measures to ensure the integrity and confidentiality of the data.

5. Conclusion

We proposed a novel approach for sentiment analysis of student comments on the Twitter platform. Our proposed approach addresses the challenges of language diversity, the presence of informal language, and the presence of emoticons, and supports three languages: English, Arabic, and colloquial Arabic. Based on ChatGPT's capabilities of addressing language nuances, we incorporated a new scoring method to build sentiment classes based on both polarity and subjectivity. Experiments conducted on real student comments dataset demonstrated the effectiveness of our proposed approach compared to conventional sentiment analysis methods.

Although the proposed approach is described and evaluated on the Twitter social platform, it can be generalized to the analysis of student comments on other platforms such as Facebook and LinkedIn. Another area of improvement could be the expansion of language support beyond English, Arabic, and colloquial Arabic. As the proposed approach is based on ChatGPT to address language nuances, the integration of additional languages is still possible. Moreover, it would be valuable to develop a user-friendly sentiment analysis toolkit or API based on the proposed approach and make it accessible to researchers, educators, and educational institutions. Further improvements of the presented work can also explore the effectiveness of recent proposed ChatGPt models, such as GPT4o and GPT4-turbo, in building sentiment scores for student comments. Conducting experimental evaluations that compare the performance and capabilities of these available ChatGPT models would provide valuable insights into their respective strengths and weaknesses in generating accurate sentiment scores in educational contexts.

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Appendix 1

In Figure A1 and Figure A2, we provide examples of calculating sentiment polarity and subjectivity scores using two different tools: TextBlob and ChatGPT (the GPT-3.5-turbo model). These examples are based on the input sentence "I absolutely love the teacher's methodology! It's amazing!". As depicted in these figures, each tool generates distinct scores, highlighting the variations in sentiment analysis results.

```
In [1]:  from textblob import TextBlob

         # Define the phrase
         phrase = "I absolutely love the teacher methodology! It's amazing!"

         # Perform sentiment analysis
         sentiment = TextBlob(phrase)

         # Extract the sentiment polarity and subjectivity scores
         polarity = sentiment.sentiment.polarity
         subjectivity = sentiment.sentiment.subjectivity


         # Print the sentiment analysis results
         print("Sentiment Polarity:", polarity)
         print("Sentiment Subjectivity:", subjectivity)

         Sentiment Polarity: 0.6875
         Sentiment Subjectivity: 0.75
```

Figure A1. Example of building sentiment and subjectivity scores using the TextBlob python library for the sentence "I absolutely love the teacher methodology! It's amazing!".

```
#initialize the sentence to be analyzed
sentence = "I absolutely love the teacher methodology! Its amazing!"

# use the defined functions for calculating sentiment and subjectivity scores based on GPT 3.5 turbo model
sentiment_score = analyze_sentiment_polarity(sentence)
subjectivity_score = analyze_subjectivity(sentence)

#print obtained scores
print("Sentiment score:", sentiment_score)
print("Subjectivity score:", subjectivity_score)

Sentiment score: Sentiment score: 0.9
Subjectivity score: Subjectivity score: 1.0
```

Figure A2. Example of building sentiment polarity and subjectivity scores using ChatGPT through the OpenAI API and using the GPT-3.5-turbo model for the sentence "I absolutely love the teacher methodology! It's amazing!"

Appendix 2

This is a simple example that demonstrates how to utilize the OpenAI API in Python to generate sentiment and subjectivity scores for a given textual sentence. The code includes two designed functions that enables the calculation of sentiment polarity and subjectivity scores based on the provided textual input sentence.

```python
"""
@author: alaa
"""
import openai

openai.api_key =
↪ 'sk-proj-O3pxTK4NoD6GZv02pDumT3BlbkFJiLacDv1wId4A4SZ5UFVM'  # My
↪ OpenAI API key

from openai import OpenAI
client = OpenAI(
  api_key=openai.api_key,
)

def analyze_sentiment_polarity(sentence):
    response = client.chat.completions.create(
      model="gpt-3.5-turbo",
      messages=[
        {
          "role": "system",
          "content": "You will be provided with a given textual
           ↪ sentence in the context of education, and your task is
           ↪ to calculate a sentiment score between -1 and 1"

        },
        {
          "role": "user",
          "content": sentence
        }
      ],
      temperature=0.2,
      max_tokens=10,
      top_p=1
    )
    sentiment_score = response.choices[0].message.content
    return sentiment_score
```

```python
def analyze_subjectivity(sentence):
    response = client.chat.completions.create(
      model="gpt-3.5-turbo",
      messages=[
        {
          "role": "system",
          "content": "You will be provided with a given textual sentence in the context of education, and your task is to calculate a subjectivity score between 0 and 1"
        },
        {
          "role": "user",
          "content": sentence
        }
      ],
      temperature=0.2,
      max_tokens=10,
      top_p=1
    )

    subjectivity_score = response.choices[0].message.content
    return subjectivity_score

#initialize the sentence to be analyzed
sentence = "I absolutely love the teacher methodology! Its amazing!"

# use the defined functions for calculating sentiment and subjectivity scores based on GPT 3.5 turbo model
sentiment_score = analyze_sentiment_polarity(sentence)
subjectivity_score = analyze_subjectivity(sentence)

#print obtained scores
print("Sentiment score:", sentiment_score)
print("Subjectivity score:", subjectivity_score)
```

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