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Multilayer Probability Extreme Learning Machine for Device-Free Localization

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Abstract

Device-free localization (DFL) is becoming one of the new techniques in wireless localization field, due to its advantage that the target to be localized does not need to attach any electronic device. One of the key issues of DFL is how to characterize the influence of the target on the wireless links, such that the target's location can be accurately estimated by analyzing the changes of the signals of the links. Most of the existing related research works usually extract the useful information from the links through manual approaches, which are labor-intensive and time-consuming. Deep learning approaches have attempted to automatically extract the useful information from the links, but the training of the conventional deep learning approaches are time-consuming, because a large number of parameters need to be fine-tuned multiple times. Motivated by the fast learning speed and excellent generalization performance of extreme learning machine (ELM), which is an emerging training approach for generalized single hidden layer feedforward neural networks (SLFNs), this paper proposes a novel hierarchical ELM based on deep learning theory, named multilayer probability ELM (MP-ELM), for automatically extracting the useful information from the links, and implementing fast and accurate DFL. The proposed MP-ELM is stacked by ELM autoencoders, so it also keeps the very fast learning speed of ELM. In addition, considering the uncertainty and redundant links existing in DFL, MP-ELM outputs the probabilistic estimation of the target's location instead of the deterministic output. The validity of the proposed MP-ELM-based DFL is evaluated both in the indoor and the outdoor environments, respectively. Experimental results demonstrate that the proposed MP-ELM can obtain better performance compared with classic ELM, multilayer ELM (ML-ELM), hierarchical ELM (H-ELM), deep belief network (DBN), and deep Boltzmann machine (DBM).

Keywords: Device-Free Localization, Extreme Learning Machine, Extreme Learning Machine Autoencoder, Multilayer Probability Extreme Learning Machine

1. Introduction

In the past decade, the widespread usage of mobile devices in the daily life has promoted the rapid development of location-based service. Hence, many localization techniques have been explored, such as wearable device, infrared sensor, and video surveillance, etc. However, those techniques require the localized entity to attach additional electronic devices or involve personal privacy, which limit their application to some extent [1, 2, 3, 4]. In order to tackle the above issues, device-free localization (DFL) was introduced as a new radio frequency (RF)-based localization approach, where the target does not need to attach any electronic device [5]. DFL can be applied to both indoor and outdoor environments, and is particularly useful in smoky, dark, and obscure scenarios, which makes it an attractive and promising technique for a variety of applications [6]. In a DFL system, radio transmitters (RTs) and radio receivers (RXs) are used as the sensor nodes to sense the target collaboratively. As the original signal field will be changed when the target enters the monitoring area, the target's location can be estimated through analyzing the changes of the signals, such as the differential received signal strength (RSS) measurements, of the corresponding links in the wireless network. In the monitoring area, theoretically, if there are s fixed sensor nodes placed along its boundary, the

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s sensor nodes will provide $s(s - 1)/2$ different wireless links in total. Among the links of the deployed sensor nodes, many links are useless and redundant, and some of them even may degrade the localization accuracy. Thus, how to extract the useful information from the links is the key to accurately estimate the target's location. In the past decade, in order to tackle this issue, many research works have tried to propose different manual feature extraction approaches to characterize the RSS of the links [7]. Accordingly, for different scenarios, it is hard to directly determine which links are absolutely more useful or useless. Thus, usually, lots of time and effort are consumed in manually extracting useful information for the specific problems. Motivated by its excellent performance in extracting features, some researchers applied deep learning approach to DFL to automatically determine discriminative features. For example, Wang et al. [8] proposed a deep sparse autoencoder to project the high-dimensional RSS data to low-dimensional feature, and obtained satisfactory performance. However, the conventional deep learning approaches, such as deep Boltzmann machine (DBM), and deep belief network (DBN), suffer from the time-consuming training process, because a large number of parameters need to be fine-tuned multiple times. Therefore, it is worthwhile to study how to apply new deep learning approach to implement fast and accurate DFL.

Different from most of the existing machine learning approaches, such as back propagation neural network (BPNN) and support vector machine (SVM), extreme learning machine (ELM) is a new training algorithm for the single hidden layer feedforward neural networks (SLFNs) [9]. The salient feature of ELM is that its hidden layer parameters are generated randomly in advance and only the output weights are required to be calculated through the least-square approach, so it can obtain much faster learning speed and better generalization performance [10]. In addition, ELM also overcomes some issues faced in most of the machine learning approaches, such as local minimum, predefining of learning rate and stopping criterion [11]. Due to the above advantages, ELM has been widely used in many real applications, such as industrial production [12], localization [13], finite-time optimal control of nonlinear systems [14], solar radiation prediction [15], etc. Theoretically, ELM has been extended to online learning [16], semi-supervised and unsupervised learning [17, 18], ensemble learning [19], imbalance learning [20, 21, 22], and residual learning [23], etc. Furthermore, considering the above shallow ELMs still face some challenges in dealing with complex tasks [24], such as image classification, voice recognition, and natural language processing, some researchers proposed hierarchical ELMs based on deep learning theory, including multilayer ELM (ML-ELM), stacked ELM (S-ELM), and hierarchical ELM (H-ELM), etc.

Considering the advantages of ELM and complexity of DFL, in this paper, we will propose a novel hierarchical ELM based on deep learning theory, named multilayer probability ELM (MP-ELM), which is stacked by ELM autoencoders (ELM-AE), for automatically extracting the useful information from the links, and implementing fast and accurate DFL. We evaluate the proposed MP-ELM-based DFL both in the indoor and the outdoor environments, by comparing it with classic ELM, ML-ELM, H-ELM, DBN, and DBM. Experimental results demonstrate that the proposed MP-ELM can obtain better performance. The main contributions of this paper can be summarized as follows:

1) A novel hierarchical ELM with probabilistic output is proposed, i.e., MP-ELM. The proposed MP-ELM consists of two phases, including the unsupervised feature representation phase and the supervised decision making phase. In the unsupervised feature representation phase, ELM-AE is implemented at each layer for extracting the useful feature layer by layer iteratively; and for the supervised decision making phase, an output layer with probabilistic estimation based on the sigmoid function is performed for the final decision making, which can avoid overfitting with better generalization performance and is more robust.

2) Different from the conventional deep learning approaches stacked by BP-based AE, ELM-AEs in MP-ELM make parameter fine-tuning not necessary in its training phase, so the learning speed of MP-ELM can be much faster.

3) The proposed MP-ELM can automatically extract useful information from the links, which not only can avoid the labor-intensive and time-consuming feature exploration procedure in the conventional DFL approaches, but also can extract more representative features with discriminative capability than the handcraft ones. In addition, considering the uncertainty of DFL, MP-ELM outputs the probability distribution of target's location instead of fitting to data, which converts the original solid classification to soft classification, and achieve better accuracy.

The paper is organized as follows. Related work is illustrated in Section 2. Preliminaries are introduced in Section 3, including the brief introduction of ELM theory and ELM-AE. Section 4 details the MP-ELM-based target's location estimation, including the motivation of proposing a hierarchical ELM with probabilistic output for DFL, the main framework of MP-ELM-based DFL, and the detailed MP-ELM. Experimental results and further analysis are reported in Section 5, followed by discussions in Section 6. Finally, conclusions and future work are given in Section

7.

2. Related Work

In this section, we will briefly introduce the related works of hierarchical ELMs and device-free localization, respectively.

2.1. Hierarchical ELMs based on Deep Learning Theory

70 As mentioned above, in order to deal with complex tasks, such as image classification, voice recognition, and natural language processing, ELM has been extended to hierarchical structure based on deep learning theory. Kasun et al. [25] attempted to a multilayer architecture using ELM autoencoder (ELM-AE) as its building block (multilayer ELM, ML-ELM), but the proposed ELM-AE requires the weights and biases to be orthogonal, which cannot guarantee the ELM's universal approximation capability. For solving large and complex tasks using ELM without incurring the
75 memory problem, Zhou et al. [26] proposed stacked ELMs (S-ELM) with multilayer structure based on the principal component analysis (PCA), which could achieve better performance with small memory requirement. As ML-ELM cannot guarantee the universal approximation of ELM, Tang et al. [27] proposed a hierarchical ELM (H-ELM) based on a L1-norm ELM-AE. Due to the use of L1 penalty, the new ELM-AE can obtain more sparse and meaningful features, and the proposed H-ELM could achieve better performance and much faster convergence speed than some
80 conventional deep learning approaches. Different from the aforementioned ELM-AEs, Zhang et al. [28] introduced a local denoising criterion to ELM-AE and proposed ELM denoising autoencoder (ELM-DAE), which can extract higher level features. Accordingly, they designed denoising Laplacian multilayer ELM (D-Lap-ML-ELM) based on ELM-DAE, which could obtain good performance in dealing with supervised learning problems. In addition, Sun et al. [29] combined ELM-AE with manifold regularization and proposed generalized ELM-AE (GELM-AE), which has
85 better representation capability for clustering. Recently, a kernel version of ML-ELM was proposed for eliminating the manual tuning and guaranteeing the generalization performance [30].

2.2. Device-Free Localization

In the past decade, different kinds of approaches have been proposed for DFL, mainly including fingerprinting and machine learning approaches, radio tomographic imaging (RTI) approach, compressive sensing (CS) approach, and
90 geometric approach, etc.

Fingerprinting approach for DFL mainly involves two phases, i.e., the offline phase and the online phase [31]. An accurate radio map is the key for obtaining good localization accuracy, which is created in the offline phase by recording the differential received signal strength (RSS) measurements of the links when the target locates at the reference points (RPs) with known positions. Aly et al. [32] leveraged an automation tool for fingerprinting
95 construction to study improved scenarios for WiFi-based DFL. Although both of the fingerprinting and machine learning-based DFL approaches are based on pattern matching, machine learning approach needs to determine the relevant parameters to build the data-driven model for DFL, while the fingerprinting approach estimates the target's location by matching the radio map. Chiang et al. [33] proposed an improved fuzzy SVM and applied it to DFL, but the undergoing SVM involves a quadratic programming problem, which is computationally expensive. Song et al. [34] proposed a scheme for DFL based on Gaussian process (GP) and particle filter, but similar to SVM, GP
100 is still time-consuming, and hard to deal with DFL with big data. In our previous work, we implemented ELM with parameterized geometrical feature extraction for fast and accurate DFL, but the feature extraction process is still manual [6]. In addition, deep learning approaches are also applied to DFL to automatically extract the useful information from the links, but those conventional deep learning approaches are time-consuming [8].

105 RTI was proposed by Wilson et al. [35] for DFL by imaging the attenuation of the target, in which the monitoring area was divided into many voxels, and each voxel has different contributions for the signal attenuation of each link. Hence, DFL can be formulated as the linear ill-posed inverse problem and solved using the regularization approach [36, 37]. Wilson et al. [38] also focused on the study of the RSS measurements in wireless networks to estimate the locations of both moving and stationary people, as well as showed the possibility of tracking more than one target.
110 Banerjee et al. [39] applied variance-based RTI to target tracking and localization, and showed the source of the unlawful activity can be identified with good accuracy. Zhao et al. [40] proposed least square variance-based radio tomography approach for DFL to reduce the negative impacts of the environment noise. Although RTI and its variants can obtain relatively good performance, the determination of some parameters in regularization highly depends on the experience, which is lack of the theoretical derivation and proof.

115 As the weights of the voxels in RTI are space-domain sparse, CS was applied to deal with the linear ill-posed inverse problem [41]. In [42], the time-of-flight measurements of the shadowed links were considered as the observation information, and a CS-based particle filter was proposed by making use of the space-domain scarcity and the time-domain scarcity. The multiple frequencies and multiple transmission power levels were used for enriching the link measurement information, and the location information of the target was reconstructed by a recursive CS approach
120 [43].

Geometric approach estimates the target's location through the geometric relationship between the target's location and the corresponding shadowed links, but it usually functions well only for the specific environment. Talampas et al. [44] proposed the multichannel geometric filter for DFL through channel diversity to diminish the effects of multipath fading of the links, and improve the localization accuracy for DFL in cluttered environment. Wang et al. [45] proposed
125 a multicarrier Fresnel penetration model for device-free localization, and obtain satisfactory performance, but its generality is relatively poor.

A Bayesian approach was proposed for DFL using the probabilistic observation information of the shadowed links, the constraint information of the non-shadowed links, and the prior probabilistic estimation information, to strengthen the robustness of the model and avoid the overfitting problem [46]. Savazzi et al. [47] studied the diffraction principle
130 to deal with the average path loss and the fluctuations of the RSS measurements induced by the moving target, and proposed a modified stochastic Bayesian approach for real-time DFL.

3. Preliminaries

In this section, ELM theory and ELM-AE are briefly introduced to facilitate the understanding of the following sections.

135 3.1. ELM Theory

Considering a learning problem of estimating an arbitrary target function with an unknown relationship between the input $\mathbf{X} \subset R^n$ and the output $\mathbf{T} \subset R^m$, that is to say, the goal of the learning problem is to find a suitable nonlinear mapping such that $\tilde{f}(\mathbf{x}) \approx \mathbf{t}$ ($\mathbf{x} \in \mathbf{X}$, $\mathbf{t} \in \mathbf{T}$) with the given dataset $\{(\mathbf{x}_i, \mathbf{t}_i)\}_{i=1}^N \subset R^n \times R^m$ with N independent and identically distributed samples.

140 As shown in Fig. 1, ELM, which undertakes a three-layer structure, was originally proposed for the SLFNs and was extended to the generalized SLFNs where the hidden layer needs not to be neuron alike. Different from other conventional approaches for training SLFNs, its hidden layer parameters (\mathbf{a}_i, b_i) are generated randomly, so the learning problem can be reduced to that of estimating the optimal output weight $\boldsymbol{\beta}$ [48].

Generally, ELM can be treated as a linear combination of L activation functions:

$$f_L(\mathbf{x}) = \sum_{i=1}^L \beta_i h_i(\mathbf{x}) = \mathbf{h}(\mathbf{x}) \boldsymbol{\beta}, \quad (1)$$

where L denotes the number of hidden nodes of ELM, and $h_i(\mathbf{x}) = g(\mathbf{x}, \mathbf{a}_i, b_i)$.

The above equation can be rewritten in matrix form as

$$\mathbf{H} \boldsymbol{\beta} = \mathbf{T}, \quad (2)$$

where \mathbf{H} is the hidden layer output matrix (randomized matrix):

$$\mathbf{H} = \begin{bmatrix} \mathbf{h}(\mathbf{x}_1) \\ \vdots \\ \mathbf{h}(\mathbf{x}_N) \end{bmatrix} = \begin{bmatrix} h_1(\mathbf{x}_1) & \cdots & h_L(\mathbf{x}_1) \\ \vdots & \ddots & \vdots \\ h_1(\mathbf{x}_N) & \cdots & h_L(\mathbf{x}_N) \end{bmatrix}, \quad (3)$$

\mathbf{T} and $\boldsymbol{\beta}$ are the target matrix and output weight matrix of ELM:

$$\mathbf{T} = \begin{bmatrix} \mathbf{t}_1^T \\ \vdots \\ \mathbf{t}_N^T \end{bmatrix} \quad \text{and} \quad \boldsymbol{\beta} = \begin{bmatrix} \beta_1^T \\ \vdots \\ \beta_L^T \end{bmatrix}. \quad (4)$$

Unlike some traditional machine learning approaches, ELM aims to reach the smallest training error as well as the smallest norm of the output weights, so its objective function can be mathematically represented as

$$\begin{aligned} \min : L_{ELM} &= \frac{1}{2} \|\beta\|^2 + \frac{1}{2} C \sum_{i=1}^N \xi_i^2, \\ \text{s.t.}, \mathbf{h}(\mathbf{x}_i)\beta &= \mathbf{t}_i - \xi_i, i = 1, \dots, N \end{aligned} \quad (5)$$

where $\xi_i = [\xi_{i,1}, \dots, \xi_{i,m}]$ is the training error vector of the m output nodes with respect to the training sample \mathbf{x}_i , C is a regularization factor for strengthening the generalization performance.

Then, based on the Karush-Kuhn-Tucker (KKT) theorem, we have

$$\beta = \begin{cases} \mathbf{H}^T (\frac{\mathbf{I}}{C} + \mathbf{H}\mathbf{H}^T)^{-1} \mathbf{T}, & N < L \\ (\frac{\mathbf{I}}{C} + \mathbf{H}^T \mathbf{H})^{-1} \mathbf{H}^T \mathbf{T}, & N > L \end{cases}, \quad (6)$$

where \mathbf{I} is the unit matrix.

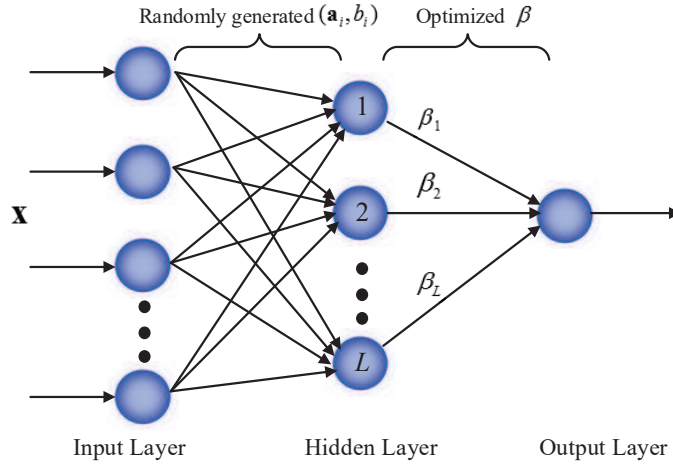


Figure 1: Basic Structure of ELM

3.2. ELM Autoencoder

Autoencoder (AE) was proposed for using the encoded output to approximate the original input by minimizing the reconstruction errors, in which the output of an AE is set to be the same as the input, i.e., $\mathbf{T} = \mathbf{X}$. AE has become a key stage in some deep architecture [49, 50, 51]. Different from the conventional AEs, in which back-propagation (BP) algorithm is usually implemented for training to obtain the identity function, Zhou et al. [26] proposed ELM-AE using ELM as the training algorithm for an AE, which is shown in Fig. 2. ELM-AE is an unsupervised neural network, in which its output is the same as the input. Thus, the input data will be reconstructed at the output layer by

$$\sum_{i=1}^L \beta_i g(\mathbf{x}_j, \mathbf{a}_i, b_i) = \mathbf{x}_j, j = 1, \dots, N. \quad (7)$$

The relationship between the input and the output can be mathematically represented in the matrix format as

$$\mathbf{H}\beta = \mathbf{X}. \quad (8)$$

The calculation of the reconstruction matrix β in three different representations can be summarized as follows:

1) Compressed representation (representing features from a higher dimensional input data space to a lower dimensional feature space, as well as the number of the input samples is more than the number of hidden nodes):

$$\beta = \left(\frac{\mathbf{I}}{C} + \mathbf{H}^T \mathbf{H} \right)^{-1} \mathbf{H}^T \mathbf{X}. \quad (9)$$

2) Sparse representation (representing features from a lower dimensional input data space to a higher dimensional feature space, as well as the number of the input samples is less than the number of hidden nodes):

$$\beta = \mathbf{H}^T \left(\frac{\mathbf{I}}{C} + \mathbf{H} \mathbf{H}^T \right)^{-1} \mathbf{X}. \quad (10)$$

3) Equal representation (representing features from an input data space dimension equals to feature space dimension):

$$\beta = \mathbf{H}^{-1} \mathbf{X}. \quad (11)$$

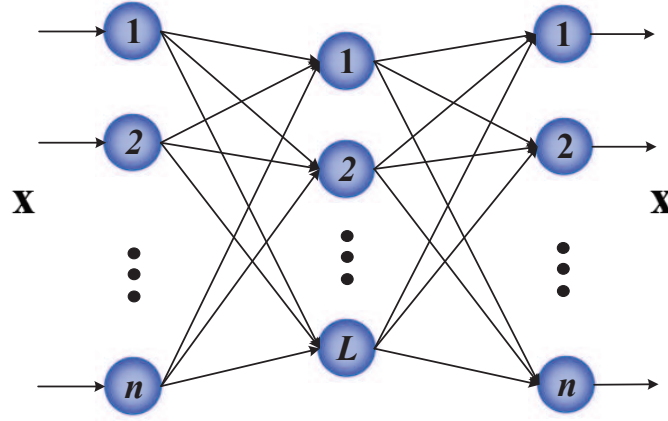


Figure 2: Structure Diagram of ELM-AE

150 4. MP-ELM-based Target's Location Estimation

In this section, we will analyze the motivation of proposing a hierarchical ELM with probabilistic output for DFL, introduce the main framework of MP-ELM-based DFL, as well as detail the proposed MP-ELM.

4.1. Motivation of Hierarchical ELM with Probabilistic Output for DFL

155 Shallow machine learning approaches have been widely used for DFL, such as SVM, GP, and ELM, but these approaches are hard to filter the useful links from the wireless networks. Because most of the links in the monitoring area are useless and redundant for target's location estimation, and some of them even may degrade the localization accuracy. In addition, due to the uncertain wireless communication environment subject to the multi-path and fade phenomena, signal transmission in the wireless network is serious uncertain, this may also result in the reference points (RPs) associate with wireless signals with large noise and further exacerbate the corruption of the data. Usually, data preprocessing and manual feature extraction approaches are performed for improving the localization accuracy. 160 However, lots of time and effort are consumed in manually extracting useful information for the specific problems. In addition, the aforementioned strategies make the data preprocessing or feature extraction and machine learning modeling become two isolated independent processes without intrinsic connection between them, which will have negative effects on the localization accuracy. In order to tackle these issues, deep learning approaches have applied 165 to DFL, and obtained satisfactory performance. However, conventional deep learning approaches suffer from the time-consuming training process, because a large number of parameters need to be fine-tuned multiple times.

Usually, DFL actually belongs to the regression problem of the machine learning field, in which the target's location can be estimated by matching the created radio map. When deep learning approaches are implemented, DFL can be converted to the classification problem (the number of classes equals to the number of reference points). In the monitoring area deploying with wireless networks, most of the links are useless for target's location estimation, which means much redundant information exists in the links. Therefore, considering the uncertainty of DFL, the deterministic approach with solid decision boundary, such as SVM, may not obtain satisfactory performance. Because if the decision making of a deterministic approach is wrong, there will be a lot of error during the localization phase, which degrades the localization accuracy significantly. However, if the decision boundary can be soft, the localization error may be reduced. In addition, the target's location only can be estimated presumably, not determined precisely, thus probabilistic approach should have better performance than the deterministic way in DFL.

When dealing with classification problem, one of the advantages of ELM is that it can be directly used for both the binary classification and multiclass classification problems. For a given testing sample, the output node with the largest decision function value denotes the class label. For the given dataset $\{(\mathbf{x}_i, \mathbf{t}_i)\}_{i=1}^N \subset R^n \times R^m$, each class label is expanded into a label vector with length m in ELM. Assuming that \mathbf{x}_i belongs to class one, so the corresponding label vector is $\mathbf{t}_i = [1, 0, \dots, 0]$.

Traditionally, for the classification problem with m classes, the output function vector of ELM classifier for a sample \mathbf{x} can be written as $f(\mathbf{x}) = [f_1(\mathbf{x}), \dots, f_m(\mathbf{x})]$, so we can determine the class label of sample \mathbf{x} by

$$\text{label}(\mathbf{x}) = \arg \max_i f_i(\mathbf{x}), \quad i = 1, 2, \dots, m. \quad (12)$$

The goal of a classifier with deterministic output is usually to minimize the Euclidean mean squared error (Emse):

$$\text{Emse} = E \|\mathbf{T} - \tilde{\mathbf{T}}\|^2, \quad (13)$$

where $\tilde{\mathbf{T}}$ denotes the corresponding estimated value of \mathbf{T} .

However, it cannot guarantee the trained ELM classifier can find the optimal solution, even if the output weight is theoretically global optimal, due to the limited capability of the given network structure [52]. Therefore, once the samples are classified with wrong labels, the classification error will be accumulated gradually.

Assuming that $\tilde{\mathbf{T}} = E[\mathbf{T}|\mathbf{X}]$ is the least square estimation of \mathbf{T} , thus, the i th component of $\tilde{\mathbf{T}}$ can be represented as

$$\tilde{t}_i = E[t_i|\mathbf{X}] = \sum_{t_i \in \{0,1\}} t_i \Pr(t_i|\mathbf{X}) = \Pr(t_i = 1|\mathbf{X}). \quad (14)$$

According to the probabilistic approach, we can obtain the probability of the samples belonging to the specific classes, thus this kind of soft classification can reduce the negative effects of classification error accumulation on ELM classifier.

Based on the above analysis, if (12) gives the wrong class label of sample \mathbf{x} , the localization accuracy will be seriously degraded. However, if ELMs (including classic ELM and hierarchical ELMs) can output the probabilistic estimation, it may be more suitable in classification with uncertainty. According to [53, 54], the output of the multilayer perceptron is actually the approximation of Bayes optimal discriminant function for classification problem. Let $f_q(\mathbf{x}, \mathbf{w})$ represent the output of the q th output node of the multilayer perceptron, w_q denotes the corresponding q th class. Based on the Bayesian theory, the discriminant function can be represented as

$$\Pr(w_q|\mathbf{x}) = \frac{\Pr(\mathbf{x}|w_q) \Pr(w_q)}{\sum_{i=1}^m \Pr(\mathbf{x}|w_i) \Pr(w_i)} = \frac{\Pr(\mathbf{x}, w_q)}{\Pr(\mathbf{x})}, \quad (15)$$

where $\Pr(\mathbf{x}|w_q)$ denotes the conditional probability, $\Pr(w_q)$ denotes the corresponding priori probability, $\Pr(\mathbf{x})$ is the probability density function, respectively. It should note that the distribution of $\{\mathbf{x}_i, \mathbf{t}_i\}$ is actually characterized by $\Pr(\mathbf{x})$.

Then, we have the following relationship:

$$\Pr(\mathbf{x}|w_i) \Pr(w_i) = \Pr(\mathbf{x}, w_i) = \Pr(w_i|\mathbf{x}) \Pr(\mathbf{x}). \quad (16)$$

Assuming that the outputs of the multilayer perceptron are restricted in 0 and 1, where 1 indicates the sample belongs to the target class, and 0 indicates it belongs to other classes. So the sample error can be represented as

$$\begin{aligned}
E(\mathbf{w}) &= \sum_{\mathbf{x}} [f_q(\mathbf{x}, \mathbf{w}) - \mathbf{t}_q]^2 \\
&= \sum_{\mathbf{x} \in w_q} [f_q(\mathbf{x}, \mathbf{w}) - 1]^2 + \sum_{\mathbf{x} \notin w_q} [f_q(\mathbf{x}, \mathbf{w}) - 0]^2 \\
&= z \left\{ \frac{z_q}{z} \frac{1}{z_q} \sum_{\mathbf{x} \in w_q} [f_q(\mathbf{x}, \mathbf{w}) - 1]^2 + \frac{z - z_q}{z} \frac{1}{z - z_q} \sum_{\mathbf{x} \notin w_q} [f_q(\mathbf{x}, \mathbf{w}) - 0]^2 \right\}
\end{aligned} \tag{17}$$

where z is the total sample number, z_q is the number of samples belonging to the class q , respectively. The average error can be represented as

$$\begin{aligned}
E_{ave}(\mathbf{w}) &= \lim_{z \rightarrow \infty} \frac{1}{z} E(\mathbf{w}) \\
&= \Pr(w_q) \int [f_q(\mathbf{x}, \mathbf{w}) - 1]^2 \Pr(\mathbf{x}|w_q) d\mathbf{x} + \Pr(w_{i \neq q}) \int f_q(\mathbf{x}, \mathbf{w})^2 \Pr(\mathbf{x}|w_{i \neq q}) d\mathbf{x} \\
&= \int f_q^2(\mathbf{x}, \mathbf{w}) \Pr(\mathbf{x}) d\mathbf{x} - 2 \int f_q(\mathbf{x}, \mathbf{w}) \Pr(\mathbf{x}, w_q) d\mathbf{x} + \int \Pr(\mathbf{x}, w_q) d\mathbf{x} \\
&= \int [f_q(\mathbf{x}, \mathbf{w}) - \Pr(w_q|\mathbf{x})]^2 \Pr(\mathbf{x}) d\mathbf{x} + \int \Pr(w_q|\mathbf{x}) \Pr(w_{i \neq q}|\mathbf{x}) \Pr(\mathbf{x}) d\mathbf{x}
\end{aligned} \tag{18}$$

Accordingly, we can find that the second term of (18) is independent with \mathbf{w} , so the multilayer perceptron is to minimize

$$E_{sum}(\mathbf{w}) = \sum \int [f_q(\mathbf{x}, \mathbf{w}) - \Pr(w_q|\mathbf{x})]^2 \Pr(\mathbf{x}) d\mathbf{x}. \tag{19}$$

Observed from the above analysis, in the limit of infinite samples, the output of the multilayer perceptron will approximate the true posterior probabilities in a least-square sense, so we have $f_q(\mathbf{x}, \mathbf{w}) \approx \Pr(w_q|\mathbf{x})$. It should note that ELM with hierarchical structure is also a kind of multilayer perceptron [27], so its output also can reflect the posteriori probabilities of different classes. Thus, theoretically, ELM with hierarchical structure with outputting the probabilistic estimation is reasonable.

4.2. Main Framework of MP-ELM-based DFL

As shown in Fig. 3, the MP-ELM-based DFL involves two phases, i.e., the offline training phase and the online localization phase. During the offline training phase, RPs are used for data collection and MP-ELM training as the samples. Each RP is associated with a number of links, and the corresponding links of all the RPs can be used for providing the training dataset. In the online localization phase, the target's location can be estimated through the trained MP-ELM-based model.

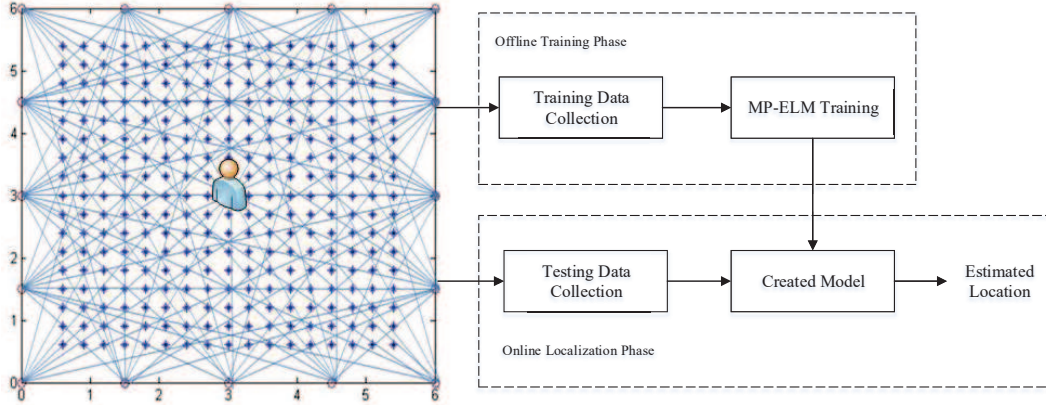


Figure 3: Main Framework of the MP-ELM-based DFL

Assuming that there are l RPs, and each RP corresponds to j RSS values, so the input matrix of MP-ELM for DFL can be written as

$$Input = \begin{bmatrix} \Delta RSS_1^1 & \Delta RSS_1^2 & \cdots & \Delta RSS_1^j \\ \Delta RSS_2^1 & \Delta RSS_2^2 & \cdots & \Delta RSS_2^j \\ \vdots & \vdots & \ddots & \vdots \\ \Delta RSS_l^1 & \Delta RSS_l^2 & \cdots & \Delta RSS_l^j \end{bmatrix}_{l \times j}. \quad (20)$$

The calculated location coordinates of the target can be represented as

$$Coordinate = \begin{bmatrix} x_1 & y_1 \\ x_2 & y_2 \\ \vdots & \vdots \\ x_l & y_l \end{bmatrix}_{l \times 2}, \quad (21)$$

where, (x_r, y_r) , $r = 1, 2, \dots, l$ denotes the target's location in DFL.

205 4.3. Multilayer Probability Extreme Learning Machine (MP-ELM)

According to the analysis in Section 4.1, we will propose a novel hierarchical ELM with probabilistic output based on deep learning theory, named MP-ELM, for automatically extract useful information from the links, and implementing fast and accurate DFL. Fig. 4 illustrates the training process of the proposed MP-ELM, which involves two phases in training its hierarchical architecture, i.e., the unsupervised feature representation phase and the supervised decision making phase. In the unsupervised feature representation phase, ELM-AE is implemented at each layer of MP-ELM for extracting the useful features layer by layer iteratively, that is to say, when the hidden layer parameters between the i th hidden layer and the $(i-1)$ th hidden layer are trained using ELM-AE, the number of hidden nodes of the i th hidden layer is identical to the number of hidden nodes of the corresponding ELM-AE. Before unsupervised feature learning, the raw data should be transformed into an ELM random feature space, which can help to exploit hidden information among training data. After that a k -layer unsupervised learning is performed to obtain the high-level useful features. The output of each hidden layer in MP-ELM can be represented mathematically as

$$\mathbf{H}_i = g(\beta_i^T \cdot \mathbf{H}_{i-1}), \quad (22)$$

where \mathbf{H}_i denotes the output matrix of the i th hidden layer, \mathbf{H}_{i-1} denotes the output matrix of the $(i-1)$ th hidden layer, and $g(\cdot)$ denotes the activation function of the hidden layers, respectively. Especially, when $i-1=0$, \mathbf{H}_1 becomes the first hidden layer, and \mathbf{H}_0 is actually the input layer of MP-ELM.

In the supervised decision making phase, an output layer with probabilistic estimation is implemented for final decision making. Considering the sigmoid function can convert an unbounded real number to a bounded real number

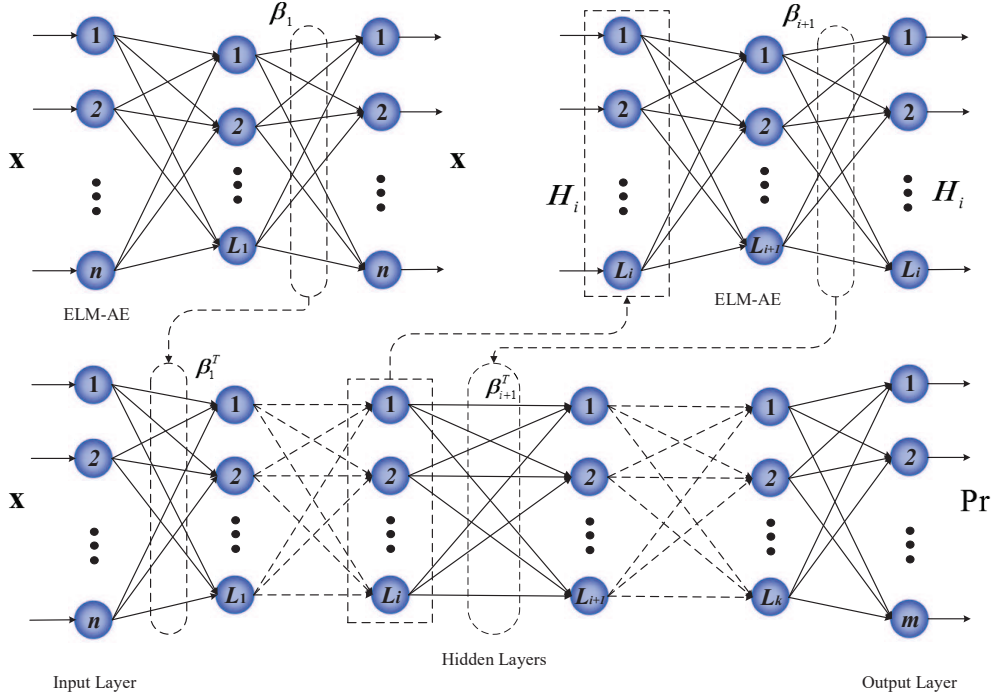


Figure 4: Training Process of the Proposed MP-ELM

between 0 and 1, that is to say, when the input approaches $+\infty$, the corresponding output will approach 1, and when the input approaches $-\infty$, the corresponding output will approach 0, therefore, we construct the probabilistic output of MP-ELM based on the basic sigmoid function:

$$\Pr(t = 1|f_q(\mathbf{x})) = \frac{1}{1 + \exp(-f_q(\mathbf{x}))}. \quad (23)$$

When the number of RPs equals to 2, MP-ELM-based DFL actually belongs to a binary classification problem, and when the number of RPs is larger than 2, it becomes a multiclass classification problem. For the binary classification problem, the sum of (23) always equals to 1, because the two outputs are opposite with each other. However, for the multiclass classification problem, the sum of (23) cannot guarantee to be 1, therefore, we normalize (23) by

$$\tilde{\Pr}(t = 1|f_q(\mathbf{x})) = \frac{\Pr(t = 1|f_q(\mathbf{x}))}{\sum_{i=1}^m \Pr(t = 1|f_i(\mathbf{x}))}. \quad (24)$$

Then, the target's location can be estimated as a weighted average of the locations of all the RPs:

$$Location = \sum_{i=1}^m \tilde{\Pr}(t = 1|f_i(\mathbf{x})) \cdot RP_i. \quad (25)$$

5. Performance Verification

210 In this section, we will evaluate the performance of the proposed MP-ELM-based DFL by comparing it with classic ELM, ML-ELM, H-ELM, deep belief networks (DBN) [55], and deep Boltzmann machines (DBM) [56]. All the simulations are carried out in a workstation with an Inter Xeon CPU E5-2620 v4 @ 2.10GHz CPU and 32G RAM.

5.1. Experimental Settings

In the experiments, we build the wireless network using CC2530 ZigBee sensor nodes, which are based on the IEEE 802.15.4 standard and operate in the 2.4 GHz frequency band. RPs are set up uniformly in the monitoring area. In the performance evaluation processes, the data from RPs are used for training model and the data from testing points (TP) for validating. Each RP provides one training sample, and each TP provides one testing sample. The RSSs are sampled at the 5-min interval, the RSS values of all the RPs and TPs are collected 100 times, and the average values of these RPs and TPs consist of the training dataset and the testing dataset, respectively. Two different experiments are performed to evaluate the proposed MP-ELM, respectively for the indoor and the outdoor environments. In addition, we use the following localization accuracy as the evaluation criteria:

$$Acc = \sqrt{\frac{1}{z} \sum_{i=1}^z (x_i - \tilde{x}_i)^2 + (y_i - \tilde{y}_i)^2}, \quad (26)$$

where (x_i, y_i) is the actual coordinates of the target, and $(\tilde{x}_i, \tilde{y}_i)$ is the predicted coordinates of the target, z is the sample number.

5.2. User Specified Parameters in MP-ELM

For classic ELM, ML-ELM, H-ELM, and MP-ELM, there are two tuning parameters, i.e., the regularization factor C , and the number of hidden nodes L . In order to obtain satisfactory performance, both of the two user specified parameters should be chosen carefully and appropriately (sigmoid function as the activation function). Fig. 5, Fig. 6, and Fig. 7 illustrate the relationship among L , C , and localization accuracy of ML-ELM, H-ELM, and MP-ELM, respectively, where L is in the search range of $\{5, 10, \dots, 200\}$, and C is in the search range of $\{2^{-20}, 2^{-15}, \dots, 2^{10}\}$. According to the three figures, we can find that ML-ELM has the fastest convergence speed, but its performance is not stable; H-ELM may be more stable, but its convergence speed is relatively slow; compared with H-ELM, the convergence speed of MP-ELM is relatively satisfactory, and it is more stable than ML-ELM.

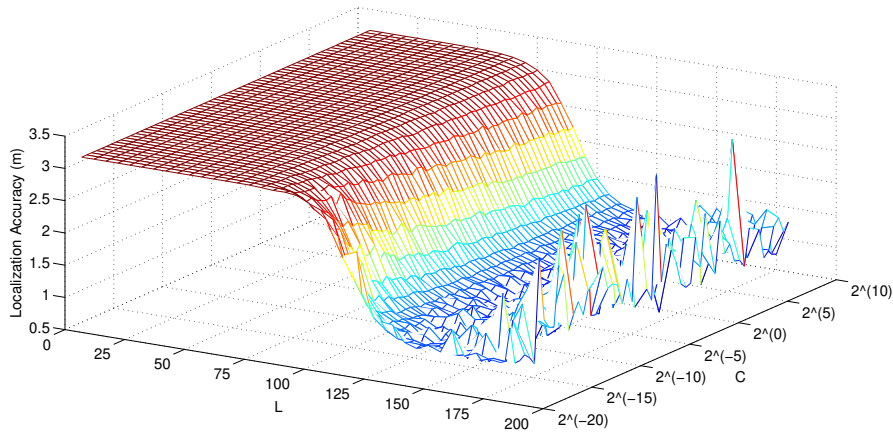


Figure 5: Relationship among L , C , and Localization Accuracy in ML-ELM

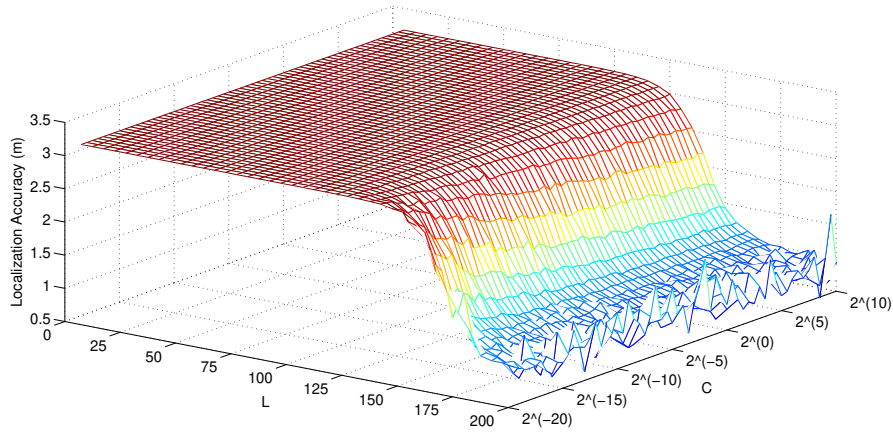


Figure 6: Relationship among L , C , and Localization Accuracy in H-ELM

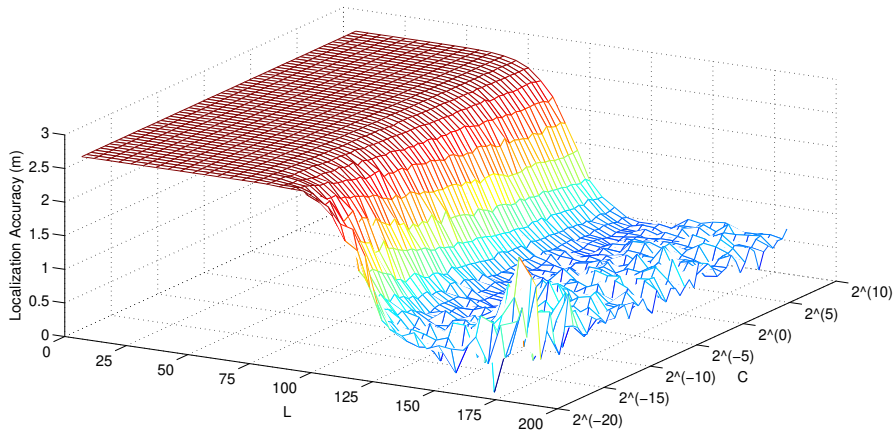


Figure 7: Relationship among L , C , and Localization Accuracy in MP-ELM

225 Table 1 lists the impacts of different numbers of hidden layers and hidden nodes on the performance of MP-ELM, including the number of hidden layers, number of hidden nodes, average localization accuracy, and time consumption. According to Table 1, we can find that the speed of MP-ELM with two hidden layers is the fastest, but its average localization accuracy is not satisfactory. With the increase of hidden layer number, the average localization accuracies become better, but more hidden layer number makes MP-ELM time-consuming gradually. Thus, we choose the three-layer MP-ELM in the following experiments as a good trade-off between localization accuracy and time consumption, whose number of hidden nodes in each hidden layer is 200, 200, and 150. In addition, in the following experiments, the hidden nodes number of ELM is set as 150; ML-ELM and H-ELM with three-layer structures are also set as 200, 200, and 150, respectively; for DBN and DBM, BP algorithm is used for training the hierarchical structures, and the initial learning rate is set as 0.1 with a decay rate 0.95 for each learning epoch.

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Table 1: Comparison Results of MP-ELM with Different Numbers of Hidden Layers and Hidden Nodes

# Hidden Layers	# Hidden Nodes	Average (m)	Time (s)
2	200-150	0.6922	0.3106
3	200-150-150	0.5791	0.5889
3	200-200-150	0.5245	0.5153
4	200-150-150-150	0.5616	0.8098
4	200-200-150-150	0.5911	0.7901
4	200-200-200-150	0.5264	0.8269
5	200-150-150-150-150	0.5330	1.1124
5	200-200-150-150-150	0.5152	1.1072
5	200-200-200-150-150	0.6588	1.5801
5	200-200-200-200-150	0.5721	1.2093

235 5.3. Evaluation in the Indoor Environment

In this section, we firstly evaluate the performance of the proposed MP-ELM-based DFL in the indoor environment. As shown in Fig. 8, the indoor environment experiment was set up in a staff activity room, and the monitoring area is a 6 m × 6 m square, with 16 nodes placed along its boundary and the adjacent node distances of 1.5 m, and 0.3 m space between adjacent RPs. We randomly choose 10 TPs for performance evaluation.

240 Table 2 details the comparison results. Accordingly, we can find that MP-ELM obtains better localization accuracies in most of the TPs, as well as the average values, especially much better than ELM. In terms of time consumption, MP-ELM, ML-ELM, and H-ELM are hundreds of times faster than DBN and DBM, so it indicates that ELM with hierarchical structure is more suitable for dealing with big data problem than conventional deep learning approaches.



Figure 8: Data Collection in the Indoor Environment

Table 2: Comparison Results in the Indoor Environment (m)

Approach	TP1	TP2	TP3	TP4	TP5	TP6	TP7	TP8	TP9	TP10	Average	Time (s)
ELM	0.6579	0.6675	0.7189	0.7067	0.9857	0.7313	1.0267	0.3559	0.5887	0.7856	0.7225	0.0692
ML-ELM	0.5316	0.5087	0.6930	0.6516	0.8066	0.6241	0.7630	0.1341	0.4029	0.7392	0.5855	0.5925
H-ELM	0.4550	0.5910	0.5853	0.6259	0.8100	0.6058	0.7201	0.1931	0.3898	0.7085	0.5685	0.3587
DBN	0.5134	0.6035	0.5505	0.6570	0.7927	0.6133	0.7035	0.1690	0.3927	0.6630	0.5659	40.3997
DBM	0.5363	0.5291	0.5271	0.6613	0.8038	0.6513	0.7110	0.1555	0.4515	0.7277	0.5755	96.2299
MP-ELM	0.4579	0.5322	0.5630	0.6095	0.7890	0.6099	0.7179	0.1399	0.4201	0.6891	0.5529	0.5896

5.4. Evaluation in the Outdoor Environment

As shown in Fig. 9, the outdoor experiment was set up on the campus of the University of Science and Technology Beijing. Similarly, the monitoring area is a $6\text{ m} \times 6\text{ m}$ square, with 16 nodes placed along its boundary and the adjacent node distances of 1.5 m, and 0.3 m space between adjacent RPs. 10 TPs are randomly chosen for evaluating the performance of MP-ELM.

Table 3 demonstrates the detailed comparison results. According to Table 3, we can find that MP-ELM obtains better localization accuracies in most of the TPs, as well as the average values. In terms of time consumption, MP-ELM, ML-ELM, and H-ELM are comparative, and still much faster than DBN and DBM.



Figure 9: Data Collection in the Outdoor Environment

Table 3: Comparison Results in the Outdoor Environment (m)

Approach	TP1	TP2	TP3	TP4	TP5	TP6	TP7	TP8	TP9	TP10	Average	Time (s)
ELM	1.2221	0.8592	1.0701	1.2297	1.5035	0.8025	1.0398	1.0187	1.5863	0.9056	1.1238	0.0527
ML-ELM	0.9517	0.6369	0.9082	1.1963	1.0512	0.8091	0.8297	1.0045	1.2162	0.6005	0.9204	0.4691
H-ELM	0.9542	0.7077	0.8385	1.1591	1.1046	0.6129	0.8923	1.0081	1.1368	0.7200	0.9134	0.2872
DBN	0.9608	0.6299	0.8880	1.0594	1.2955	0.5927	0.9599	1.0967	1.1009	0.7540	0.9338	43.1863
DBM	0.8335	0.6012	0.8263	1.0052	1.0970	0.6568	0.8556	1.0207	1.0328	0.6527	0.8582	90.5007
MP-ELM	0.8657	0.6129	0.7042	1.0036	1.0898	0.5033	0.8208	1.0229	1.0393	0.6717	0.8335	0.3542

6. Discussions

In some conventional deep learning approaches, the parameters of all the hidden layers need to be determined iteratively using BP algorithm, so the training process is time-consuming and cumbersome [57]. However, in the proposed MP-ELM, once the features of the previous hidden layer are extracted, the parameters of the current hidden layer will be fixed, and need not to be fine-tuned. Therefore, the learning speed of MP-ELM is much faster than some conventional deep learning approaches. In the experiments, ELM is chosen as one of the comparison approaches. Unlike some deep learning approaches, there is no automatic feature extraction in ELM [58]. According to the experimental results, the localization accuracies of MP-ELM as well as other selected deep learning approaches are much better than ELM, which indicates that the feature extraction plays a central role in deep learning. In addition, ELM is much faster than others due to its single-hidden-layer structure. However, ELM cannot function well in dealing with complex tasks, that is to say, ELM may be more suitable for simple tasks with big data. In those kinds of cases, ELM can obtain both satisfactory accuracy and little time consumption. For complex tasks with big data, MP-ELM is much faster than some conventional deep learning approaches, but with comparative accuracy.

Most of the links in the monitoring area are useless and redundant for target's location estimation, that is to say, DFL belongs to the task with uncertainty. When we use the classifier with solid decision boundary, if the samples are

classified with wrong labels, the classification error will accumulate gradually during the localization phase, which seriously degrades the localization accuracy. However, if we use MP-ELM, which is with probabilistic output, the decision boundary will be soft, we can obtain the probability of the samples belonging to the specific classes, so it can reduce the negative effects of classification error accumulation on the final localization accuracy. Thus, the proposed MP-ELM has better performance than other deep learning approaches. In general, MP-ELM has three advantages: 1) it can reduce the chance of overfitting of the model by estimating the probability of samples' attribution instead of fitting the samples; 2) it can reduce the error accumulation through the weighted average of the probability of the target's location belonging to all the RPs; 3) it can enhance the reliability of the classifier through integrating hierarchical ELM with probabilistic approach. It should note that, to our best knowledge, the proposed MP-ELM is the first hierarchical ELM with outputting the probabilistic estimation.

As mentioned above, one of the advantages of MP-ELM is the randomly generated hidden layer parameters, which makes it have very fast learning speed. Simultaneously, it also leads to the instability of MP-ELM. Because the randomization of the hidden layer parameters has significant impacts on the performance of ELM-AE. ELMs are actually sensitive to the range, and the change of the range may decrease the stability of MP-ELM. Unfortunately, there is still no clear and theoretical criterion to guide the selection of the randomization range for different datasets. Usually, the randomization range is set as a specific interval, but different data have different distributions, so the results of MP-ELM may fluctuate in the specific range [59, 60, 61]. The theoretical analysis and experimental results indicate that MP-ELM is more suitable in dealing with large-scale and complex problems than some conventional deep learning approaches. Because the high time consumption of those deep learning approaches makes some short-term problems meaningless, such as advertisement click ratio prediction and stock price prediction, etc.

7. Conclusions

In this paper, MP-ELM is proposed for automatically extracting useful information from the links, and implementing fast and accurate DFL. MP-ELM is stacked by ELM-AEs, and outputs the probabilistic estimation instead of fitting to data, so it has very fast learning speed as well as good generalization performance and robustness. Compared with the conventional manual approaches for feature extraction in DFL, MP-ELM can automatically learning discriminative features from the links with less labor and time consumption. Compared with some conventional deep learning approaches, the learning speed of MP-ELM is much faster. In addition, different from the existing hierarchical ELMs, MP-ELM outputs the probabilistic estimation, but not the deterministic value, so it is more suitable in dealing with the complex tasks with uncertainty, such as DFL. Comprehensive experiments demonstrate the validity of the proposed MP-ELM-based DFL. This paper only considers the localization problem with single target, so the future work will address the multi-target localization problem.

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