ÓBUDA UNIVERSITY

Ph.D. Dissertation
-Thesis Book-

Soft Computing Methods for Classification Problems in Intelligent Space

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Abstract

So-called "*Smart environments*" are a popular tool for humans to collect information, form the environment, get assistance, etc. The Intelligent Space (iSpace) is one such system that offers various services for improving the comfort and safety of everyday life. The main and ultimate goal is to build an environment that is human centered, comprehends human interaction and provides various services.

The goal of my research thus far has been introducing new methods that can extend the toolkits available for the iSpace, providing additional functionalities in fields such as hand gesture detection, color-based object or human user tracking, etc.

In Thesis I., I present a new hand posture detection method for man-machine interfaces in iSpace. To reliably describe human hand postures, I have designed so-called Fuzzy Hand Posture Models (FHPMs, Thesis I.1) that use 14 distinct features. The inputs of the system are provided by a system that detects the outline of the hand using two cameras and describes the shape by the coordinates of 14 3D points. In order to map these 3D points to 14 fuzzy sets I have developed a *new neural network structure* named *Circular Fuzzy Neural Networks* (CFNNs, Thesis I.2), which are a trimmed and fuzzified variant of Artificial Neural Networks. The output of the neural network is then classified using fuzzy inference. The performance of the method has been shown for 6 different hand postures.

During the development of the hand posture recognition system, one problem was the complexity of the CFNNs. Complexity is generally a very important factor for neural networks, which typically scales with the number of

dimensions of the problem. It is a significant problem for the CFNNs as well: the time requirement for training (with the general neural network back propagation algorithm) scales significantly with the number of input samples (considering the high dimensionality of the hand detection problem), even with the reduced complexity gained from the connection trimming. To solve this problem and thus further enhance the training speed of Artificial Neural Networks (such as the Circular Fuzzy Neural Networks), I have introduced a new clustering method which, as the conducted tests proved, is capable to create a more compact representation of training data sets.

I have also designed a new control system framework for the Intelligent Space, as well as a new graph-based knowledge representation method for storing a priori knowledge in the system. Based on commands given by the user, the system creates hypotheses (a posteriori knowledge), i.e. a presumed connection between given commands and the circumstances (the measured values during the detection of the command), so the system is capable to learn and automatically issue commands that have been observed enough times (e.g. *making coffee at 8:30 on weekdays*). Its effectiveness has been observed in a virtual iSpace room where the daily life of one inhabitant is simulated.

During the development of the clustering algorithm mentioned above, I had the idea of not only using clustering to reduce the amount of training samples, but to train the structure of Radial Basis Function (RBF) networks directly: setting the center and width parameters of each neuron to a resulting clustering center. The output of each neuron can be gained by calculating the Gaussian function using its parameters and a given input value, providing a metric about how likely the input value is to belong to the cluster. If all neurons are evaluated and the one with the largest output is chosen, then we can find the cluster that is closest to the input data. Thus, I have created a new rule-based classifier called *Fuzzy Filter Network* (FFN) that essentially realizes a fuzzy inference (where a rule consists of the center and width values of each cluster, as well as the class it belongs to). I have also developed a new algorithm called *Analytical Radial Representative clustering method* in order to train the FFN, as well as *a parallelized version* that reduces the necessary training time of the classifier using parallel computing techniques. The classification performance of the filter network using the proposed clustering algorithm as training, as well as that of the parallel version have been shown through a color filtering experiment.

Although the FFN is a very useful tool for classification, its computational requirements make it less efficeint for real-time color filtering. In order to solve this problem, I have developped a new classifier called *Fuzzy Hypermatrices* (FHMs), based on the idea of mixing lookup table classifiers and fuzzy logic. The method uses a multidimensional array structure to store precalculated fuzzy membership values for each point of the problem space, assigning a likelihood value of them belonging to a given class. This reduces the operation time of the evaluation to a single array access, resulting in a very fast operational speed at the cost of memory space. The method can easily parallelized as well, classifying each input data (i.e. pixels of an image) concurrently. I have validated the efficacy of the classifier for both the sequential and parallel versions on color filtering problems.

Even though FHMs provide a very fast operation, their memory requirement bars them from being used in problems

where the problem space is of higher (more than 4) dimensions. In order to solve this problem, I have designed the so-called Sequential Fuzzy Indexing Tables, that use the same principle as the FHMs, but break down the multidimensional problem space into a sequence of 2D arrays, forming a layered architecture where each layer uses one input attribute value and one index value (gained in the previous layer). Starting from the first layer, the evaluation progresses layer by layer, and in the last layer the class label can be found. I have designed a fixed-length and a variable-length version for the classifier, so it can be used for data in which the length of each of the data samples can be different. The efficacy of the proposed methods has been tested on benchmark data sets and compared to that of other state of the art classifiers, as well as a practical application (a dietary advisor application).

1. Introduction

In recent decades, with the spreading of machine intelligence, "*smart environments*" have become a popular tool for humans to collect information, form the environment, get assistance, etc. The Intelligent Space (iSpace) [*Lee et al, 2000*] is an intelligent environmental system that offers various services for improving the comfort and safety of everyday life as well as for achieving personalized healthcare and independent living for disabled persons. The main and ultimate goal of such systems is to build an environment that is human centered, comprehends human interaction and satisfies them [*Lee et al*, *2004*].

The iSpace, which has been developed at the University of

Tokyo, is a special intelligent implementation of the Ubiquitous Computing paradigm [*Weiser, 1991*] and a variant of the widely known "Smart Environment" (e.g. "Smart Home") frameworks. Intelligent Space can be any smart area such as a room, railway station, underpass, road crossing, or even a whole town, that is equipped with intelligent sensors and agents. The main feature of the iSpace is that the intelligence itself is not present in the agents but it is distributed in the whole space. The main advantages of this component based architecture are that the iSpace can easily be constructed or modified by the installation or replacement of so-called Distributed Intelligent Networked Devices (DINDs) responsible for monitoring a part of the space, processing the sensed data, making local decisions, and communicating with other DINDs or agents if necessary. Thus, a further advantage of such a system is that the agents in the space do not have to possess any complex logic.

Any room or area can be converted to an iSpace by installing DINDs into it. Although, when building iSpace into an existing area we have to keep in view that the system should be human centered, should not be disturbing for the people who are using it and the installation should not alter the area overly. Another important feature of the iSpace is that it builds models of the environment; it can observe the events and actions taking place in the room or area and is able to react to them if necessary, in order to achieve some kind of change or give information to the users, help in orientation or anticipate crisis situations. It can also comprehend human interactions: the user can give commands to the Intelligent Space to use certain services. Therefore, the system should be easy to use for the people in it, without the need for them to spend much time learning about how the system is to be used.

2. Research Aims and Their Relevance in the Context of the State of the Art

The Intelligent Space is a widely researched framework. Numerous new methods and applications have been developed for it since its establishment. Robot control [*Morioka et al, 2002*] is one of the central areas in iSpace research: [*Brscic et al, 2009*] has proposed a mapping method for the robotic agents of the iSpace, [*Jin et al, 2006*] has developed a human following mobile robot control using the data of distributed sensors, while [*Hwang et al, 2007*] has proposed an obstacle avoidance method for car-like mobile robots. [*Galambos et al, 2011*] has described a new virtual iSpace control framework, while in [*Vanijjirattikhan et al, 2005*] an intercontinental iSpace setup is described that has been created between the Hashimoto Lab at the University of Tokyo in Japan and the Advanced Diagnosis Automation and Control Lab at North Carolina University in the USA, in which a mobile robot in the former laboratory was controlled by a path-tracking controller in the latter one, etc. [*Jeni et al, 2006*][*Jeni et al, 2007*] and [*Jeni et al, 2009*] have developed a mobile agent control system using reinforced learning. [*Zanaty et al, 2009*] has created an image based object localization method, then has proposed facial expression recognition system in [*Jeni et al, 2012*] using near infrared cameras. [*Yokoi et al, 2008*] have developed a hand localization method that uses ultrasonic and inertial sensors, while [*Niitsuma et al, 2006*] have introduced the design of spatial memory, in which knowledge is assigned to given areas of 3D physical space, which can be recalled on command (by pointing a finger at it). [*Niitsuma et al, 2008-1*] have proposed an observation system that can track human activity regarding given objects, then expanded on the idea to develop a method that localizes objects by observing the physical interaction a human user has with it. In [*Niitsuma et al, 2008-2*] this idea has been expanded upon, incorporating human-object interactions in it as well. Subsequently, [*Niitsuma et al, 2009*] has extended it with visual and vibration displays.

[*Ichikawa et al, 2012*] has created a new method for ethologically inspired human-robot interaction, which has been expanded on by [*Takahashi et al, 2015*], who proposed an attachment behavior model for social robots in the iSpace. [*Ichikawa et al, 2018*] has developed an ethologically inspired nonverbal human-robot communication method for ambient assisted living applications. [*Palafox et al, 2009*] has proposed a human movement profile classifier using Self Organized Maps [*Kohonen et al, 1982*], then has developed a human activity recognition system using conditional fields [*Palafox et al, 2011-1*] and particle swarm optimization [*Palafox et al, 2011-2*].

The goal of my research thus far has also been introducing new methods that can extend the toolkit available for the iSpace. For this, I had developed a new hand posture detection method that I have developed for a gesture-based man-machine interface (Thesis I) in the iSpace; a new clustering method for reducing neural network training time (Thesis II), a general iSpace control system framework (Thesis III) and various classification methods (Theses IV-VI) for pattern recognition.

3. Research Methodology

During the course of my research, I have validated the efficacy of the newly developed methods on different computers, mainly using different versions of Microsoft Visual Studio (using C++) and Matlab. For methods where the operation is accelerated using parallel computing techniques, I have applied Nvidia CUDA. Furthermore, many of the benchmark data sets I have used for testing have been taken from the UCI Machine Learning Repository.

4. New Scientific Results and Theses

In this section the *Theses* will be shown and in the sub-sections their detailed description is given.

4.1. Hand Posture Modeling for Intelligent Space Applications

Thesis I.1: *I have proposed a new fuzzy hand posture model that uses a fuzzy feature set consisting of 14 features over 3 feature groups. I have also developed a new hand posture detection method for the identification of hand postures.*

Thesis I.2: *I have developed a new neural network structure named Circular Fuzzy Neural Network.*

4.1.1. Detailed explanation of Thesis I

Thesis Group I presents a new hand posture detection method for a gesture-based man-machine interface. To reliably describe human hand postures, I have developed so-called

Fuzzy Hand Posture Models (FHPMs, Thesis I.1) that use 14 distinct features [T1-1]-[T1-5].

The input of the proposed method is provided by an image processing system ([Tóth et al, 2009]) that uses two cameras and a Fuzzy Matching Algorithm to calculate the 3D coordinates of the shape of the hand. In order to convert these coordinate points to FHPMs, I have introduced a new neural network structure named Circular Fuzzy Neural Networks (CFNNs, Thesis I.2) for the processing of the 3D coordinate points. CFNNs are a trimmed and fuzzified variant of Artificial Neural Networks (ANNs, [27]). In order to achieve a fuzzy neural network [28], a pair of ANNs is used to approximate the lower and upper bounds of each fuzzy [29] membership function value. To reduce the increased training time requirement that is caused by the doubled complexity of the network, the number of connections between the input layer and the hidden layer neurons are reduced: each input coordinate value is given to only 3 neighboring hidden layer neurons. The first and the last hidden layer neurons are considered neighbors as well, hence it is a circular structure. The output of the method is the label of the hand posture model that is the most similar to the detected one, considering its shape. Since the proposed fuzzy hand posture feature set consists of 14 features, three separate CFNNs are used to map the 15 input coordinate triplets into 5-5-4 outputs. The resulting 14 fuzzy features (represented by the lower and upper interval limits) are processed with a fuzzy inference machine that finds the closest known hand posture to it. The performance of the method has been shown for 6 different hand postures, on which the conducted experiments have shown a 96% classification precision on average.

4.2. A New Clustering Method for the Acceleration of the Training of Artificial Neural Networks

Thesis II: *In order to enhance the training speed of Artificial Neural Networks, I have introduced a new supervised Neural Network training method including an input sample clustering step.*

4.2.1. Detailed explanation of Thesis II

Complexity is a very important factor for neural networks, which typically scales with the number of dimensions of the problem. It is a significant problem for Circular Fuzzy Neural Networks as well: the time requirement for training (with the general neural network back propagation algorithm) scales significantly with the number of input samples (considering the high dimensionality of the hand detection problem), even with the reduced complexity gained from the connection trimming. In Thesis II, to further enhance the training speed of Artificial Neural Networks, I have introduced a new clustering method [T2-1]-[T2-4]. The proposed method is based on the *k-means* method, but instead of creating *k* clusters and assigning every sample into cluster with the nearest mean value, it groups each sample (in the order the data is received) with the rest of the samples that are closer than an arbitrary similarity factor d, and returns the center of each group. The method has been shown to decrease training time significantly, at the cost of a slight decrease in classification precision, depending on a similarity factor δ used in the clustering algorithm. Smaller δ values generally result in less training time reduction but also a lesser degree of loss in classification accuracy. The new method has been evaluated for Artificial Neural Networks, Radial Basis Function Networks and Circular Fuzzy Neural Networks.

4.3. An Intelligent Space Control System Framework

Thesis III: *I have developed a new iSpace Control System (iSCS) framework consisting of intelligent detection modules, command processor modules, and autonomous action planner modules, together constituting a smart environment system that can provide services to users based on the available resources and agents. I have also designed and implemented a new graph-based knowledge representation system to describe a priori knowledge for control systems.*

4.3.1. Detailed explanation of Thesis III

I have proposed a new control system framework for the Intelligent Space in Thesis Group III, and introduced a new graph-based knowledge representation schema for storing a priori knowledge [T3-1]-[T3-6]. The latter is designed as a graph-based structure, where each individual node represents a concept or action. The nodes are homogeneous, their identification is done through dictionaries that assign labels to each, thus ensuring language independence. The relations between the concepts are described through edges between their respective nodes, making it possible to store and retrieve complex information (the a priori knowledge) in the system. Based on observed commands given by the user, it creates hypotheses (a posteriori knowledge). Each hypothesis is bound to one or more conditions and each time the system observes the same command in under very similar circumstances (e.g. around the same time of the day) then the reliability factor of the hypothesis is increased. If the given conditions are met for a sufficiently reliable hypothesis (with reliability factor exceeding an arbitrary threshold) then its command is automatically issued by the system. Its effectiveness has been observed in a virtual Intelligent Space where the daily life of one inhabitant is simulated, giving the iSpace orders according to his or her needs and the system learns to satisfy them automatically.

4.4. Adaptive Fuzzy Rule-based Classification with Fuzzy Filter Networks

Thesis IV.1: *I have proposed a new fuzzy rule-based classification method called Fuzzy Filter Networks that is based on a topological modification of Radial Basis Function neural networks. I have also introduced a new clustering algorithm called Analytical Radial Representative clustering in order to train the new fuzzy rule-based classifier. The algorithm follows the bottom-up approach.*

Thesis IV.2: *I have designed a parallel realization of the new Fuzzy Filter Network classifier, which reduces the complexity of both the training and the operation of the classifier.*

4.4.1. Detailed explanation of Thesis IV

The focus of **Thesis Group IV** is *a new rule-based classifier called Fuzzy Filter Network* [T4-1]-[T4-3], based on a modified RBF neural network architecture (**Thesis IV.1**). The base idea is that instead of calculating the activated linear combination of the input data (like in the case of an RBF network), the proposed method realizes simple pattern matching by using the radial basis functions for proximity detection, then simply choosing the class or label associated to the pattern (characterized by the center and width parameters of the basis functions) as output. This classifier has the advantage of being very simple to implement, train (by clustering) and modify the trained knowledge (by adding or removing patterns).

Furthermore, I have designed a new clustering approach for the training of the fuzzy filter network: the *Analytical Radial Representative clustering* method. The algorithm implements a so-called bottom-up approach, calculating the appropriate cluster radiuses in a single phase. The efficacy of the thus trained network is shown through various experiments.

Beside the sequential implementation, *I have designed a parallel realization* as well (**Thesis IV.2**) [T4-4], which reduces the computational complexity of both the training (down from $O(P{\cdot}N{\cdot}m)$ to $O(N{\cdot}m)$) and the operation (down from $O(P{\cdot}N)$ to $O(P)$) of the classifier (considering N attributes and P samples). The classification performance of the filter network using the proposed clustering algorithm as training, as well as that of the parallel version have been shown through a color filtering experiment.

4.5. Real-time Classification with Fuzzy Hypermatrices

Thesis V.1: *I have introduced Fuzzy Hypermatrices, a new classification method that extends lookup table classifiers in order to achieve a fast and robust classifier. I have introduced generalization ability to the method by implementing Fuzzy logic implicitly into the structure.*

Thesis V.2: *I have developed a parallel version of the FHM classifier that is able to process images with a significantly lower time complexity than that of the sequential version, and provide a more stable classification performance than pFFNs.*

4.5.1. Detailed explanation of Thesis V

The focus of Thesis V is about a new lookup table [*Campbell-Kelly et al, 2003*] based classifier called Fuzzy Hypermatrices [T5-1]-[T5-4], that is extended with fuzzy logic. The method maintains multi-dimensional arrays that store the precalculated class labels and fuzzy membership function values for all input attribute value combinations. The input attribute values are directly used to address the array. It achieves a very fast and simple classification, with the downside that it requires a significant amount of memory to operate (scaling with the number of attributes and the size of their domains), thus its applicability is restricted to problems with low dimensionality, such as color filtering (in HSV or RGB color spaces). Besides the sequential version, I have also designed and implemented a parallelized version of the method [T5-5], which has been shown to an even (~51-71 times) faster color filtering.

4.6. Real-time Classification with Sequential Fuzzy Indexing Tables

Thesis VI.1: *I have expanded upon the idea of Fuzzy Hypermatrices and developed a new classifier named Sequential Fuzzy Indexing Tables for real-time classification of complex problems with a constant number of dimensions (c-SFIT).*

Thesis VI.2: *I have extended the Sequential Fuzzy Indexing Tables classifier to work on variable length data (v-SFIT).*

4.6.1. Detailed explanation of Thesis VI

Although FHM classifiers realize a very fast operation, their memory requirement significantly limits their usage options. The focus of Thesis 6 is a fuzzy classifier called **Sequential Fuzzy Indexing Tables** (constant length SFIT or c-SFIT [T6-1]-[T6-3]) that uses a sequence of one 1D and N 2D fuzzy lookup tables in to achieve a more memory-efficient classification than FHMs on problems with a constant number (N) of attributes. It has a layered structure, where each layer contains a lookup table that combines the value of an attribute belonging to that layer to the combination gained in the previous layers. Thus in each layer, the proposed method reduces the size of the problem space in which the class of the input pattern is. This significantly reduces the size of the array structures needed to be stored in the memory, compared to FHMs. The performance of the classifier has been tested on benchmark data sets and compared to that of other state of the art classifiers. The proposed classifier performs with slightly less precision but faster than the other methods.

Furthermore, in Sub-thesis VI.2. I have extended the Sequential Fuzzy Indexing Tables classifier to work on variable length data as well (v-SFIT) [T6-4].

5. The Practical Applicability of the New Scientific Results

The presented *hand posture models* and the *hand posture detection system* are directly designed for hand gesture-based man-machine communication interfaces. In such systems various the hand gestures can be bound to commands and the user can instruct the system to carry out various functions. E.g. in a hospital setting, the nurse who is making the rounds during the night shift could just gesture with her hand to have the system automatically turn off the lights or open doors in her way, without the need to touch any surfaces, or make a classic control gesture (e.g. clapping) that would be noisy and bother the patients. Such gestures can be detected even in the dark using UV light cameras.

Among the prominent practical applications for my proposed *clustering method* in iSpace applications, there is passive space exploration through activity monitoring (e.g. automatically discovering places with given functionalities in the home environments, hospitals, public parks, etc., by simply observing that the users have spent longer periods of time in such places). Traffic control is another important field in which a good estimation about places with higher load, along with the rough measure of the load can help alleviating the problems caused by high traffic. The primary goal for the iSCS framework is to provide services to the users, or more precisely, to act as a services broker between the user and various executive agents. Another practical application of the system could be helping the cooperative work of robotic agents in the iSpace, e.g. coordinating the routes that cleaning or transportation

robots take in a facility based on the layout of the rooms and the capabilities of each robot (e.g. can traverse stairs, etc.).
Although the primary purpose of the *FFN classifier* was color-filtering, the classifiers I have made after it have been shown to be more effective (much faster). On the other hand, the FFN classifier is a simple, easily configurable fuzzy inference system, which can be used for any practical applications that require a rule-based classifier (e.g. software quality classification).
The main, practical application for the *FHM classifier* is real-time color filtering, which it performs with a high efficiency according to the conducted experiments.
And lastly, I have applied both of the *SFIT classifer* types successfully in an iSpace-based dietary assistant application that uses a c-SFIT for storing food items based on their nutrition data and a v-SFIT for storing the names of food items [T6-5][T6-6].

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