Computational intelligence systems and applications

Final Report
(K108405)

The five years of the project covered several areas of Computational Intelligence, especially Fuzzy Systems, Evolutionary and Memetic Algorithms, and Artificial Neural Networks; often combining two or three in a single research stream.

The research was connected with several PhD students' and postdoctoral fellows', and in a few cases, with MSc students' research and thesis project. In the period of this research the following students have successfully their completed PhD degrees (in D170):

- Gergely Molnárka,
- Adrienn Buruzs,
- Áron Ballagi,
- Alex Tormási,
- Ferenc Lilik.

Postdoctoral fellowships (Pál Erdős, Széchenyi István University Mobility, New National Excellence Program) for research connected to this project were received by the following:

- Ádám Bukovics,
- Szilvia Nagy,
- Miklós Hatwágner.

The following PhD students are currently participating in connected research:

- Boldizsár Tüű-Szabó (New National Excellence Program),
- Kata Vöröskői,
- Brigitta Szi,
- Gábor Farkas (status pending),
- Laili Yuhana (visiting student),
- Zainal Fanani (visiting student),
- Silvia Chaparro Cardenas (visiting student),
- Julian Andres Ramirez Bautista (visiting student).

The following new PhD students were enrolled from 1 September, based on earlier involvement in the project research:

- Gergely Fogarasi,
- Ruba Mahasneh (in D136).

The following MSc students have actively participated in the research:

- Rita Amro,
- Saransh Dhama,
- Aliia Rysbekova,
- Youyang Wan,
- Gergely Fogarasi (now enrolled as PhD student),
- István Polt.

In the next, the main research streams where results have been achieved (and publications issued) will be briefly overviewed:

1. Fuzzy operators

   Study of fuzzy Hamacher-operators, their role in the construction of fuzzy neural networks, convergence properties in learning, use in fuzzy rule extraction. The advantages of this operator family are their continuity and smoothness, and especially, their strictly monotonic behavior (which enables inversion under certain conditions).

   The application of bacterial evolutionary and memetic algorithms for optimizing fuzzy rule bases. Investigating several types of benchmark problems, it turned out that the bacterial memetic algorithm family, especially in the extraction of fuzzy production rules outperformed other approaches published earlier in the literature.

   Although the above rather complex topic was mainly connected to the research in the previous project, some of these results were further used in the mainstreams forming the backbone of this five year project.

2. Fuzzy signatures

   Fuzzy signatures (FSigs) had been introduced by the chief investigator in the past. FSigs may be represented by rooted trees with fuzzy membership degrees on the leaves (or by nested fuzzy membership vectors).

   One of the main directions of this project was the study of mathematical properties of FSigs (an extension of the original definition of fuzzy membership). The advantage of FSigs is the possibility of hierarchically arranging various more or less connected features of certain elements of the universe, and the possibility of doing manipulations on FSigs with partly missing components. The idea of the "family of a basic FSig" was introduced, and operations on members of such families were defined and investigated. Among others, the Hamacher-operators mentioned in Section 1 were also applied on FSigs, with extended membership degree ranges (real-valued fuzzy sets). In this particular application, the strict monotonicity of the Hamacher-family was rather important, as the inversion of the operators was applied in the calculation of certain modifying factors in application a). This extension of FSigs was necessary for certain applications (see below).

   One of the main result groups in connection with FSigs referred to the mathematical sensitivity of the root membership degree in terms of the uncertainty at the leaves of the FSig. The sensitivity was investigated especially for two classes of operators: the Hamacher-class and the special non-commutative operations created in application a).

   Another theoretical advancement in this area was the introduction and study of fuzzy signature state machines. These latter are suitable for dynamically modeling the time dependent conditions in hierarchical fuzzy descriptors. Fuzzy signature state machines consist of a structural FSig containing fuzzy state machines (the fuzzy extension of finite state machines) in every leaf. The fuzzy states of the resulting FSig state machines are defined as the Cartesian product of all these component states, however the "participation" of each state component corresponds to the hierarchic position of the component automaton, and evaluation of the values (conditions and costs) happens with help of the aggregations in the FSig. Any state transition in such a resultant automaton is

assigned an overall cost, which influences the strategy of planning a series of state transitions between two states (start and goal).

Another extension of the FSig concept was the idea of fuzzy situational maps (in 2D and 3D). Various operations, like "zoom in" and "zoom out" and combination of such maps by fuzzy operators were studied. The introduction of the special operations on the fuzzy situational maps was strongly influenced by the targeted applications (b) and c).)

The relation of the algebraic structure of FSig families and operations with Goguen's L-fuzzy structure has been as far only partly established. Intensive research has been going on in order to define a pair of suitable lattice join and meet over the set of all members of a family of FSigs, corresponding also to real life application needs. (Jointly with the Dept. of Mathematics, University of Cadiz). As far no such pair has been found and it is very likely now that the algebra of FSigs is more general than the algebraic lattice.

Recently, the idea of nesting FSigs sets into sparse fuzzy rule bases was also investigated and an algorithm for applying rule interpolation on homogenous FSig set rule bases was proposed. Interpolation in such homogenous systems under the preservation of the FSig structure is possible if the "scale and move interpolation algorithm" of Q. Shen is involved. Further research is going on in the frame of the next project how this interpolation technique may be extended to heterogeneous FSigs, particularly to FSigs within a family.

FSigs have been widely applied for modeling and manipulating various engineering systems. The following main application areas have been studied, where new methodological results have been also achieved.

a) The modeling and evaluation of the condition of residential buildings. This is a typical application for FSigs, as in the available large database (district archives collections on Budapest historical buildings) verbal and vague (fuzzy) evaluations are given, where civil engineering considerations also determine the hierarchical structure of FSigs applied. An interesting product of this application was the definition of several new non-commutative aggregations, corresponding to engineers' experience.

These new aggregations served as starting points for the mathematical sensitivity results being part of the theoretical research in this field. Another new task was the optimization of planning the renovation of a given building or group of buildings.

This application possibility triggered the idea of fuzzy signature state machine. The (partial) renovation of a single building, or a group of buildings may be modeled by a corresponding FSig state machnine. The renovation costs strongly depend on the state transition path (the sequence of renovation steps), and thus finding an optimal path under given conditions may be essential in the real life. Here, the application of evolutionary approaches was proposed, but as far no algorithm for this extremely complex problem has been established. (One successful PhD defense not yet mentioned, Ádám Bukovics, was entirely based on this joint research.)

b) Another ongoing application was the communication and collaboration of mobile robots, based on fuzzy signatures in the original form and on fuzzy situational maps. (The ongoing postdoctoral research of Awad Sirair is closely connected with this topic.)

c) 3D fuzzy situational problems in warehouses initiated the idea of spatial FSigs, which also led to a real life, namely logistics (warehouse optimization) application (based on the data obtained from a multinational radiator factory).

d) A more recent application was the evaluation of (primary school) educational data. In this sub-project, rough sets were also combined with FSigs. This research is going on in collaboration with the Sepuluh Nopember Institute of Technology in Surabaya.

3. Fuzzy rule bases

Fuzzy rule interpolation, and particularly hierarchic fuzzy rule interpolation has been always in the focus of attention of the chief investigator. While a series of theoretical and algorithmic results had been already published by this research group, an entirely new approach for evaluating high dimensional vague data had been proposed in the frame of this research: the combined application of wavelet transform, and fuzzy rule interpolation. Two rather different potential application areas of this new method led to the formulation of this novel CI approach:

- The evaluation of real life measurement data on telecommunication copper wire pair capabilities (for predicting data transfer band width).
- The evaluation of colorectal images (for detecting polyps).

Both applications were based on large pools of real life data. In the first case, actual measurements on wire pairs carried out by the PhD student amounted to 400,000 data obtained. In the second case, three sets of colonoscopy images, coming from three various types of equipment, obtained from a hospital had been used. The results in the first application were superior to all other approaches, and the method proposed also had the great advantage that only a very restricted number of measurements were necessary when applying this method.

While in the second application promising results were obtained on high pixel images, still the precision of the classification results needs further investigation, which is going on in the frame of the next project. Here, especially feature extraction, such as edge detection, of the filtered images may help increase the precision of the classification. (Unfortunately, bad quality images coming from an old style colonoscope have not yet delivered good results.)

4. Fuzzy Cognitive Maps

The research of Fuzzy Cognitive Maps (FCM) has been continuously going on, with considerable results.

a) The original motivating example for applying (FCM) was the modeling of the sustainability of waste management systems. In the literature, a single six concept model has widely been applied for such environmental management systems. As historical data for Hungary were available, it was obvious to compare these data, i.e. the FCM fitting them, with the FCM obtained from the six concept model and corresponding mutual influence values. The results were very much contradictory.

As an explanation, the inadequacy of the simple model was identified, and by consultations with various experts, a considerably larger number (33) of concepts (or sub-concepts) were identified. While such a large FCM model might adequately describe the behavior of such a complex system of systems, it is impossible to determine the mutual

influence values (directed edge weights) of 33x32 connections, as no expert of any field may properly estimate so many fine connections. The real solution of the problem of searching for a sustainable state (i.e. a fixed point attractor of the FCM) could be determining an FCM model with more than six and definitely less than 33 concepts (between 10 and 15, maybe 20). In order to obtain a tractable size FCM from the refined model, a new FCM concept reduction algorithm was proposed. In order to check the applicability of the new models, virtual historical data were constructed by text mining of relevant documents of several decades of the past, where keywords of each 33 concept were systematically identified.

b) Our new algorithm raised several new questions. To what degree did the behavior of the reduced FCM match the behavior of the original, large size model? Did the reduced model preserve the value(s) and the number of fixed point attractors, and did the reduction preserve stability at all? Did the parameter determining the learning speed of the FCM affect the answers to the previous questions? In the subsequent project years, a series of answers were given, partly by numerous simulations, by applying the new algorithm on several reference benchmark data, and on a large amount of randomly constructed test FCM-s. Results confirming the usability of the reduction algorithm were published and at the same time, several interesting new mathematical problems were identified.

c) By the theoretical investigation of the fix point behavior of the FCMs it was recognized that uncertainty in determining the concept state values and/or the influence degrees could have an effect on the very number of steady states, even on the limit behavior of the FCM (convergent, periodical, chaotic). The sensitivity analysis of the FCM limit behavior, and its combination with the investigation of parameter sensitivity also resulted in several new results to be published. One of the most interesting results of this mathematical investigation was that a generally accepted theorem (widely referred to in the literature) was false, its published proof containing a mistake.

d) Besides the theoretical research, several application oriented investigations were carried out. Here the following should be mentioned:

- management systems of Hungarian and Lithuanian companies, with a comparison of behavior
- bank management systems
- circular economy
- user interface design

5. Fuzzy approach to character recognition

Connected to topic 3, but applying a rather different concrete approach, fuzzy rule base systems were also applied for hand written character recognition. While some preliminary results had been obtained during the past years, in the frame of this project, the optimization of the parameters of such rule based character classifiers came in focus of the investigation. Besides the Bacterial Memetic Algorithm, several others, such as the Imperialist Competitive Optimization Algorithm, the Big Bang-Big Crunch and a new method called Fungal Growth have been tested and compared. The first single stroke characters were extended to multiple stroke characters. As an interesting side step, we attempted to apply similar methods for classifying the types of wild animal movements. (Alas, too few data were available.)

6. Fuzzy recommender systems

Fitting the above wider toolkit, we also attempted to apply fuzzy weights and fuzzy rule based models in various social networks and recommender systems. The first application example was a model of how to recommend movies to a given subscriber (family) based on the habits of watching TV programs. In this research, unfortunately, no real life database could be obtained. In social networks, however real data from Twitter and a certain internet group game were used for developing an efficient recommender and behavioral prediction system. Our paper on the latter obtained the Best Paper Award by the International Fuzzy Systems Association and Japan Society for Fuzzy Systems.

7. Meta-heuristic for solving NP-hard problems

The sub-topic where evolutionary and memetic algorithms were applied for solving highly complex (NP-hard) problems, namely, for finding (quasi-) optimal solutions for such problems proved to be one of the most successful areas. While the research of various evolutionary and population based algorithms has been going on throughout the whole project (cf. Section 3), where the complex result awarded by the IEEE Best Paper Award also included bacterial memetic optimization; from the 3rd project year, we opened research towards discrete memetic techniques. (The antecedent project already produced some promising initial results in connection with two types of logistics related NP-hard tasks.) The first reference problem class dealt with the Travelling Salesman Problem (TSP). The classic tailor made solution was the Lin-Kernighan (LK) heuristics, which however turned out to be too slow in the case of large reference problems (with over 1000 nodes). The CONCORDE algorithm produces exact optimum but fails to stop for > 4000 nodes. The most recent and most efficient algorithm is Helsgaun's extension of the LK. We attempted to achieve this speed and accuracy by improving the local search in the Discrete Bacterial Memetic Evolutionary Algorithm (DBMEA), however as far the speed of the tailor made Helsgaun method could not yet be beaten (except for very few reference problems, where the Helsgaun is too slow). DBMEA is, however, considerably better than the other two in terms of predictability.

In the next, the following further (related, but essentially different) NP-hard problems have been investigated by searching DBMEA solutions.

Abstract problems:
- Traveling Salesman Problem with Time Window (TSP TW)
- Time Dependent Traveling Salesman Problem (our approach is likely the best practice in the moment, TDTSP)
- Traveling Repairman Problem (our approach is far the best practice in the moment, TRP)

In the TSP TW the solution produced by DBMEA again preformed somewhat worse than the best practice known form the literature. (A tailor made solution entirely different from the previous ones.) However, in the TDTSP task DBMEA performed very well, and it is likely better than the other approaches published in the literature. (The problem of comparing lies in the fact that there have been no general runtime results made accessible for the competing best tailor made heuristics.) Eventually, in the TRP task DBMEA turned out to be far the fastest and most accurate approach for the solution.

While in the four problems classes there are entirely different tailor made methods, known, which are only applicable for the particular problem class, thus they lack any general applicability, DBMEA can solve all four problem types with acceptable speed and accuracy, even in the cases of a better approach existing, still delivering acceptable good solutions in acceptably short time. The great advantage of DBMEA is its universal applicability. No other such generally usable method has been as far published in the literature.

One more advantage of DBMEA is the better predictability of the runtime in terms of the size of the problem instance. We introduced the concept of efficacious heuristics, being efficient, predictable and general in the applicability. In the ongoing and connected research project we will further investigate efficacious algorithms.

Besides the bacterial evolutionary algorithm family, we have investigated other population based methods, such as the Fungal Growth, Teaching-Learning, Predator-Prey and the Squirrel algorithms.

8. Application problems

As a "side product" of the research, various applications of the CI techniques investigated were carried out: recommender systems, social network applications (with one Best paper Award from IFSA), material science, etc.

9. Other related activities

Based on the results summarized above, the Chief Investigator has been invited as the editor of several contributed books and conference proceedings (three already published, two in production), further, invitations as Lead Guest Editor, and Guest Editor at various impact factor journals; and several survey and historical articles have been written, partly in IF journals (focusing on fuzzy and Computational Intelligence research and methodologies).

The summary publication result of the project is 19 journal papers (mostly with impact factor, in one case IF= 7.4), three edited volumes (two more in print), 28 book chapters, 76 peer reviewed conference papers and four peer reviewed conference abstracts. (Further submitted papers have been accepted since the end of the project period.)

Budapest, 24 September 2018

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