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Perspectives in Fuzzy Logic and Fuzzy Systems

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This special issue on fuzzy systems and fuzzy logic applications appears in a context that deserves attention. Big Data and Deep Learning advances seem to increasingly favor statistical approaches to uncertainty and imprecision, while one year passed since Lotfi Zadeh, the initiator of fuzzy logic and systems passed away. These evolutions may shadow, even hamper the progresses in fuzzy systems. To assess how much or whether the methods based on fuzzy logic are still relevant, we turned toward research article databases. A search on WOS [1] has produced interesting results for the discussed topic. The number of papers on fuzzy systems has not flatlined during the last decade; the variation is linear, ($y = 397.8x + 5060.1$, $R^2 = 0.84$), with a slope of almost 400 papers per year (Fig. 1a), while for the last seven years the linear variation has a larger slope ($y = 546.6x - 1E + 06$, $R^2 = 0.964$, Fig. 1b). However, while healthily increasing, the growth of the domain is only linear. Compare that with the increase of the number of papers in neural networks (NNs), which was boosted by the inception of 'Deep Learning': in recent years, the number of papers[2] on NNs has increased exponentially ($y = 2E - 99e0.1177x$, $R^2 = 0.957$), see Fig. 1b.

[1] Searched for TOPIC: (fuzzy system*), timespan: each year in the last decade, Indexes: SCI-EXPANDED, SSCI, AHCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC.

[2] Data was collected on WOS at the beginning of October 2018.

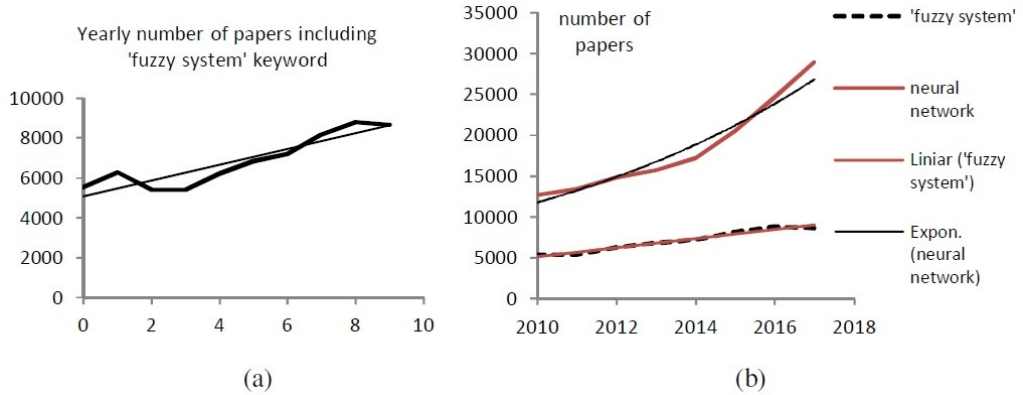

Fig. 1. (a) The yearly change of the number of papers reported in WOS between 2009 (0 on the axis) and 2017 (corresponding to 10). (b) Comparison of FL and NN numbers of papers, 2010-2017.

Since 2009, this Journal published only a handful of papers [3] on applications of fuzzy logic systems (FLSs), with only one during the first two years, namely [11]. In fact, the average number is less than one paper per year. Five of these papers were published during the last three years. For comparison, there are 24 articles on applications of neural networks during this period, in this Journal. Other fields pertaining to A.I. and related branches of computer science are also limitedly represented; there are only eight articles on clustering, eight on speech (voice) technology, five on cellular automata, and two on swarm-based methods. Therefore, the encouragement of the Chief Editor of the publication of a special issue with papers pertaining to fuzzy logic applications is both very judicious and reassuring.

Currently, in *deep learning*, the main NN architecture is that of large number of interconnected convolutional NNs [3], one layer convolving the results of previous ones. The hybrid field of *deep learning* and *fuzzy systems*, named shortly *fuzzy deep learnin*g (FDL), has started to develop less than five years ago; a precise year could be 2014, when for the first time more than five papers have been published. There are already several excellent papers in the field, for example [1], [9], [10]. The number of papers on *fuzzy deep learning* increased exponentially ($y = 0.69e0.533x$, $R^2 = 0.89$), but as far as in 2017 the number of papers published on FDL was less than 100.

The versatility of the fuzzy logic methods in the myriad of applications they have seen until now is mainly due to the power of representation (approximation). They may require some tedious, or hidden, automatic tweaking of the membership functions and rules, such as in the ANFIS method (Adaptive Network/Neuro- Fuzzy Inference System), but they are able to represent any reasonable function, i.e., control surface in terms of automatic control. This general description of the representation power is in fact a set of results (theorems) by several authors published in the 1990s and proving that fuzzy logic systems (FLSs) with centr-of-gravity defuzzifier are *universal approximators* for continuous functions $R^n \rightarrow R^m$, on bounded intervals. On the other hand, often the optimal control or decision function (surface) is unknown, hence the learning of the approximating system is required as an essential feature. In these situations, the computational burden of the FLSs, which is comparable with that of the NNs, but is higher than

[3] Precisely, ten papers. Statistic based on WOS, $Search.do?product = WOS\&SID = D4nh7Z4dAcdVEFYwtLW\&search\_mode = GeneralSearch\&prID = 7711b106 - ae93 - 4ce9 - a86a - d106e566701c$.

that for other approximation methods such as splines, is a potential disadvantage.

From these fundamental properties follow applications such as modeling of imprecise and unknown systems, illustrated in this issue by the paper 'Experiments in Incremental Online Identification of Fuzzy Models of Finger Dynamics', by R.-E. Precup et al., who show how to develop evolving TSK fuzzy models for the human hand (finger) dynamics, with application to the control of prosthetic hands. Also related to modeling is the paper 'Fuzzy logic approach for temperature analysis in multi-jet air impingement investigation', by Priya, Chandramohan, and Kannan. The applications in control are in addition exemplified by Labdai et al. in the paper 'Sliding mode control via fuzzy multi-level switching control scheme for DFIG based WECS', while an application of fuzzy logics in decision making is illustrated by the paper authored by Karali et al. All these papers are highly applicative, with the solution in the last paper integrated in a commercial software package. The paper by Karali et al. also draws the attention not only because the problem of optimal packing is hard and the authors solve as well the choice of a most suitable package out of a given set, but also the solution involves a compelling way to assign fuzzy loading capacities to the specified containers. On the other hand, while the solution proposed by Labdai et al. is viable, it is not totally convincing in the way of using the approximation power of FLSs, as discussed above, because of the use of basic types of membership functions for the variables. The paper by Priya et al. was also chosen for its strong applicative flavor and the importance of the multi-jet heat transfer modeling, although we are convinced that significant improvements in the heat transfer efficiency can be obtained by improving the model and the analysis in this paper, among others using more intricate adaptive fuzzy models, as discussed below and demonstrated in other papers in this issue.

The *universal approximators* results mentioned above have justified why to use fuzzy systems, but they have not shown how to apply them. In fact, the degree of complexity of the operations and computations needed for achieving a specified accuracy of representation may be, for fuzzy logic systems with defuzzification, higher than the complexity involved by spline functions or even neural networks. We have previously proved that basic approaches to adjusting fuzzy logic systems for approximating a continuous function $R^n \to R$ with an error less than ε is of the order of $(\frac{a}{\varepsilon})^n$, where a is a constant depending on the length of the definition interval (along one dimension) and the maximum of the partial derivatives of the function (gradient components). The appealing trait of fuzzy logic remains mainly its intuitive description, while the advantages of FLSs include their flexibility of being combined with NNs and with various other biology-inspired systems and with varied adaptation methods, as illustrated by almost all papers already mentioned and specifically by the paper by Dobrea and Dobrea in this issue; these authors demonstrate the advantages of using CANFIS (Co-active Adaptive Neuro-Fuzzy Inference System).

Beyond the approximation power of FLSs, there is another reason why fuzzy logic became so popular, namely its roots in infinite-valued logics (Lukasiewicz logics) and its ability to promote other fundamental tools for dealing with uncertainty and fine-grained information [6]. Many extensions of 'non-standard' fuzzy logic and fuzzy sets have been introduced, including the possibility theory by Dubois and Prade [2], numerous related infinite-valent logics based on t-norms and s- co-norms (see [4], [5]), probabilistic fuzzy sets, intuitionistic fuzzy sets, Pythagorean fuzzy sets [8], complex fuzzy sets [7], etc. In line with this direction is the paper 'An extension of ELECTRE to multi-criteria decision making problems with extended hesitant fuzzy sets', by Zhao and Huangy, published in the present special issue. Recalling that in a hesitant fuzzy set there are multiple possible membership degree of the elements, and that extended hesitant fuzzy

sets are basically sets whose elements have a membership degree a Cartesian product of sets of possible membership degrees, one can state the contribution of Zhao and Huang as introducing and analyzing outranking relations on such sets and then building an ELECTRE approach based on extended hesitant fuzzy sets.

In the same theoretical direction is in this special issue the paper by Ngan et al., on definitions and properties of complex (fuzzy) t-norms and s-norms. After recalling some related definition, including that for complex fuzzy sets, sets with complex-valued grade of membership η, which are used among others in time series forecasting, these authors define the complex *t*-norm on the fuzzy unit disk D as a mapping $D \times D \to D$ which is commutative, associative, monotonic in the module and argument, and satisfies $T(p, 1) = p, \forall p$. Then, these authors verified that the new concepts have the desirable properties known for t-norms and conorms and used the defined the complex t-norm and conorm for developing and demonstrating an algorithm for multi-criteria decision making.

I hope that the readers of this Journal will enjoy this special issue and also I hope to see this trend in publishing special sections in fuzzy logic continued by the Journal, moreover complemented by special sections in other domains of IA. We look forward to have soon a special issue on FDL. Prospective authors are welcomed to send manuscripts on this and similar topics to the Journal.

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