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On the Development of Signatures for Artificial Intelligence Applications

Claudiu Pozna
Department of Informatics and Department of Automation and Information Technology
Széchenyi István University and Transilvania University of Brasov
Győr, Hungary, and Brasov, Romania
cp@unitbv.ro

Radu-Emil Precup
Department of Automation and Applied Informatics
Politehnica University of Timisoara
Timisoara, Romania
radu.precup@upt.ro

Péter Földesi
Department of Logistics and Forwarding
Széchenyi István University
Győr, Hungary
foldesi@sze.hu

László T. Kóczy
Faculty of Engineering Sciences and Department of Telecommunications and Media Informatics
Széchenyi István University and Budapest University of Technology and Economics
Győr, Hungary, and Budapest, Hungary
koczy@sze.hu

***Abstract*—This paper illustrates developments of signatures for Artificial Intelligence (AI) applications. Since the signatures are data structures with efficient results in modeling of fuzzy inference systems and of uncertain expert systems, the paper starts with the analysis of the data structures used in AI applications from the knowledge representation and manipulation point of view. An overview on the signatures, on the operators on signatures and on classes of signatures is next given. Using the proto fuzzy inference system, these operators are applied in a new application of fuzzy inference system modeled by means of signatures and of classes of signatures.**

***Keywords*—Artificial Intelligence; expert systems; knowledge representation; proto fuzzy inference systems; signatures**

I. INTRODUCTION

The signatures are data structures which can be successfully used systems modeling. The signatures have been defined in [1] as a generalization of fuzzy signatures [2] as convenient hierarchical symbolic representations of data structured into nested vectors of fuzzy values. The main advantages of fuzzy signatures are the compact representation of complex structures when used in fuzzy modeling and the suitability in using heterogeneously determined information (i.e., with partly missing components). A thorough discussion on fuzzy signatures in data mining is conducted in [3], and medical and robotics applications are given in [4] and in [5], respectively.

The paper will start with an analysis of the data structures used in Artificial Intelligence (AI) applications from the knowledge representation and manipulation point of view. These two issues refer also to the technological (manipulations) and to the conceptual (representations) aspects of AI implementations. Other implementation areas including control engineering are characterized by unitary data (signal) and system representations as, for example, the Laplace and Z transforms. These representations allow for algebraic manipulations and also provide powerful synthesis algorithms.

The originality of the paper is the presentation of the theoretical elements that enable the development of signatures for AI applications. The paper is constructed on the basis of signatures, classes of signatures and operators on signatures proposed in [1] and on their applications in modeling of fuzzy inference systems [1] and of uncertain expert systems [6]. The paper proposes a new application of signatures which models a fuzzy inference system using the proto fuzzy inference system.

The structure of our paper is organized in four sections: the mentioned analysis is presented in the next section. Section III gives next an overview of signatures, of classes of signatures, of definitions and of their related basic operators used in data manipulation. The application which deals with a fuzzy inference system modeling by means of signatures is offered in Section IV. The conclusions and future work intentions are discussed in Section V.

II. DATA STRUCTURES IN KNOWLEDGE REPRESENTATION AND MANIPULATION

As shown in [7], knowledge is a true sentence about something. For our purpose the interesting aspect of this definition is represented by the possibility to obtain a conceptual representation of the knowledge expressed as specific data structures.

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A data structure is valuable if it allows for complex information representation and manipulation. Several data structures have been proposed during the AI development, and they include semantic networks, scripts and frames [8], [9]. Each of these data structures allows complex information representation, but they have the same drawback: no runtime structure manipulations are defined or possible at all. From a technological implementation point of view the concepts of frames and scripts lead to object-oriented (OO) programming. Objects are defined as computational systems with encapsulated state, methods are associated with this state, supporting interactions in an environment [10]. The only widely accepted way of representation for objects is offered by UML diagrams which however allow mainly a graphical interpretation.

The knowledge is transformed by systems in terms of rational processes transformations in the cognitive paradigm [11] or in terms of mechanism transformations in the embodiment paradigm [12]. Each transformation is performed by a particular system using a known technique as, for example, fuzzy logic, neural networks, decision trees, etc. From the representation point of view these transformations are in most cases algorithms and the knowledge is expressed as scalars, vectors or matrices. This reflects an important issue, namely the non-unitary representations in AI. This issue has been recognized and accordingly treated considering several solutions as Lisp or Prolog programming languages [13]. Unfortunately these solutions are only technological, but they do not go deeper into the methodological layer. No analytical support is provided in order to help the system synthesis in an algebraic form and no automation of software design and code generation by high level formal methods are provided.

Investigations related to the cognitive theory have been directly connected with the representation and knowledge management [11]. In cognitive informatics, logic, linguistics, psychology, software engineering, and knowledge engineering, concepts are identified as the basic unit of both knowledge and reasoning [14]. The formal theories as concept algebra or visual semantic algebra have been proposed in [15], [16] for concept manipulations and for the development of a rigorous semantics of UML as an industrial OO design language.

Alternative strategies have continued to question the role of explicit representation of knowledge for example in the subsumption architecture [17]. A future stage of development in representation can be found in Computation Intelligence (CI) that superimposes the notation of sub-symbolic information on well established structures in AI [18], [19].

The modeling of complex systems needs various ways to handle the complexity and the uncertainty [20]–[23]. Several modeling issues from engineering points of view are addressed in [20]. Tools and applications related to linguistic decision making are overviewed in [21]. A combination of prediction and classification is discussed in [22] and expressed as an optimal adaptive voting strategy. A prototype-based rule inference system that incorporates linear functions is proposed in [23].

Fuzzy logic and fuzzy modeling have gained widespread applications in the context of uncertainty modeling in complex systems [24]–[27]. Multidimensional generalized fuzzy integrals and applications to the definitions of indices are discussed in [24]. The state of knowledge on propositional fuzzy logics is surveyed in [25]. An experimental study on kernel-based fuzzy clustering and fuzzy clustering is conducted in [26]. Image compression modeling results based on fuzzy transforms of monotone functions are offered in [27]. Some current applications of fuzzy logic and modeling include process control [28]–[47] with focus on predictive and adaptive fuzzy control [28], [29], combinations between fuzzy control and sliding mode control [30]–[33], type-2 fuzzy logic [34]–[39], data-driven tuning of fuzzy controllers [40], [41], tensor product-based model transformation [42]–[44], and self-evolving fuzzy control [45]–[47]. Appropriate derivative-based and nature-inspired optimization techniques [48]–[65] can be employed in combination with fuzzy modeling and control.

Modeling in AI is the subject of several paradigms, and cognition [66] and embodiment [67] are two such recent representative paradigms. Each of them has advantages and drawbacks. A common drawback of all these paradigms is that no unitary representation in modeling can be offered as a general shortcoming of other theoretical AI paradigms. Several questions arise after the study of the current stage of AI / CI modeling: Could a common representation for knowledge and systems be found such that to transform this knowledge in to a regularized form? Would such an attribute (the unitary representation) be beneficial? And, if it is true, where can the advantages been observed? Is it possible to imagine the algebra of OO programming which is unitary with the representation of the model?

This literature analysis outlines that these issues have been recognized recently, and that several solutions start to be constructed. We suggest the use of signatures which have been proposed and exemplified in AI algorithm synthesis as shown in [1] and [6].

III. Overview on Signatures, Classes of Signatures and Operators on Signatures

Signatures and operators on signatures are defined and discussed in [1]. A part of the definitions which enable the modeling of expert systems is presented in this section, and the reader is invited to address [1] and [6] for the analysis of several examples in order to understand the concept of signatures. Let $S^{(n)}$ be a set defined recursively as

$$S^{(n)} = \prod_{i=1}^{n} S_i,\ S_i = \mathbf{R} \text{ or } S_i = S^{(m)},\ m \geq 1,\ i = 1 \ldots n, \quad (1)$$

where $\mathbf{R}$ is the set of real numbers, and Π is the Cartesian product.

Definition 1. Let X be a nonempty set. The *collection of signatures* is defined as the function $A : X \to S^{(n)}$, the *signature* of the element $x \in X$ is $A(x) \in S^{(n)}$, and the *transposition* of the signature $A(x)$

$$A(x)=\begin{bmatrix} \ldots \\ a_i \\ \begin{bmatrix} a_{i+1,1} \\ a_{i+1,2} \end{bmatrix} \\ \begin{bmatrix} a_{i+2,1} \\ \begin{bmatrix} a_{i+2,2,1} \\ a_{i+2,2,2} \end{bmatrix} \end{bmatrix} \\ \ldots \end{bmatrix} \tag{2}$$

is $A^T(x)$

$$\begin{gathered} A^T(x)=[\ldots \quad a_i \quad [a_{i+1,1} \quad a_{i+1,2}] \\ [a_{i+2,1} \quad [a_{i+2,2,1} \quad a_{i+2,2,2}]] \quad \ldots]. \end{gathered} \tag{3}$$

A set of notations described as follows is introduced in [1] to simplify the mathematical characterization of signatures. A signature $A(x)$ with values

$$a_1, a_2, \ldots, a_n, a_{i,1}, a_{i,2}, \ldots, a_{i,m}, \ldots a_{j,k,l}, \ldots \tag{4}$$

is indicated by $a^{\cdots}$. The notation

$$A(x)=a^{1,\ldots,n} \tag{5}$$

is used if

$$\exists x \in X,\ A^T(x)=[a_1 \quad \ldots \quad a_n]. \tag{6}$$

If

$$\begin{aligned} &\exists y \in Y,\ A^T(y) \\ &=[a_1 \quad \ldots \quad a_{i-1} \quad [a_{i,1} \quad \ldots \quad a_{i,m}] \quad a_{i+1} \quad \ldots \quad a_n], \end{aligned} \tag{7}$$

we will use the notation

$$A(y)=a^{1,\ldots,[1,\ldots,m]_i,\ldots,n}. \tag{8}$$

The sets are defined as

$$S_1=S_2=\ldots=S_{i-1}=S_{i+1}=\ldots=S_n=\mathbf{R}, \tag{9}$$

and their Cartesian product is

$$\prod_{i=1}^{m} S_i=\prod_{i=1}^{m}\mathbf{R}=\mathbf{R}^m. \tag{10}$$

A signature of type

$$[\ldots \quad [[a_1]] \quad \ldots],\ a_1 \in \mathbf{R} \tag{11}$$

is equivalent to the signature $[a_1]$.

Definition 2. A class of signatures is a set of signatures with the same structure. In the following this structure is named the *signature tree*, and it is indicated by the symbol $\hat{a}^{\cdots}$. This means that each signature $a^{\cdots}$ has an associated signature tree $\hat{a}^{\cdots}$.

The symbol S is used to indicate *the set of all signatures* and the symbol $\hat{\mathrm{S}}$ will be used to indicate *the set of all signatures trees.* For example, these notations are

$$a^{1,2,\ldots,n} \in \mathrm{S},\ \hat{a}^{1,2,\ldots,n} \in \hat{\mathrm{S}}. \tag{12}$$

As shown in [1], the signatures can be used in complex data representations. Some definitions of operators on signatures will be exemplified in the sequel using the information from [1] and [6].

Definition 3. The *contraction* of a signature is defined as one of the three functions

$$\begin{aligned} &{}^f@:\mathrm{S}\to\mathrm{S},\ {}^f@(a^{1,2,\ldots,n})=a^1=[a], \\ &{}^f@_i:\mathrm{S}\to\mathrm{S}, \\ &\begin{cases} {}^f@_i(a^{1,\ldots,[1,\ldots,m]_i,\ldots,n})=a^{1,\ldots,i,\ldots,n}, & \text{if } i\le n, \\ {}^f@_i(a^{\cdots})=a^{\cdots}, & \text{otherwise}, \end{cases} \\ &{}^f@_{\mathrm{i,j,k}}:\mathrm{S}\to\mathrm{S}, \\ &\begin{cases} {}^f@_{\mathrm{i,j,k}}(a^{1,\ldots,[1,\ldots,[1,\ldots,[1,\ldots,q]_k,\ldots,r]_j,\ldots,m]_i,\ldots,n}) \\ =a^{1,\ldots,[1,\ldots,[1,\ldots,k,\ldots,r]_j,\ldots,m]_i,\ldots,n}, & \text{if } i\le n, j\le m, k\le r, \\ {}^f@_{i,j,k}(a^{\cdots})=a^{\cdots}, & \text{otherwise}, \end{cases} \end{aligned} \tag{13}$$

where

$$\begin{aligned} &a=f(a_1,a_2,\ldots,a_n),\ f:\mathbf{R}^n\to\mathbf{R}, \\ &a_i=f(a_{i1},\ldots,a_{im}),\ f:\mathbf{R}^m\to\mathbf{R}, \\ &a_{i,j,k}=f(a_{i,j,k1},\ldots,a_{i,j,kq}),\ f:\mathbf{R}^q\to\mathbf{R}. \end{aligned} \tag{14}$$

Extra indices can be inserted after *i*, *j* and *k*, to generalize this definition. The following notation is proposed for the absolute value of a contraction if a has the first form in (13):

$$|{}^f@(a^{1,2,\ldots,n})|=a. \tag{15}$$

Definition 4. The *extension* of a signature is defined as one of the functions

$$\begin{aligned} &{}^g\overline{@}_{\mathrm{i}}^{\mathrm{p}}:\mathrm{S}\to\mathrm{S}, \\ &\begin{cases} {}^g\overline{@}_i^p(a^{1,2,\ldots,i,\ldots,n})=a^{1,2,\ldots,[1,\ldots,p]_i,\ldots,n}, & \text{if } i\le n, \\ {}^g\overline{@}_i^p(a^{\cdots})=a^{\cdots}, & \text{otherwise}, \end{cases} \\ &{}^g\overline{@}_{\mathrm{i,j,k}}^{\mathrm{q}}:\mathrm{S}\to\mathrm{S}, \\ &\begin{cases} {}^g\overline{@}_{i,j,k}^q(a^{1,\ldots,[1,\ldots,[1,\ldots,k,\ldots,r]_j,\ldots,m]_i,\ldots,n}) \\ =a^{1,\ldots,[1,\ldots,[1,\ldots,[1,\ldots,q]_k,\ldots,r]_j,\ldots,m]_i,\ldots,n}, & \text{if } i\le n, j\le m, k\le r, \\ {}^g\overline{@}_{i,j,k}^q(a^{\cdots})=a^{\cdots}, & \text{otherwise}, \end{cases} \end{aligned} \tag{16}$$

where two forms of the function g are used,

$$g:\mathbf{R}\to\mathbf{R}^p,\ g(a_i)=[a_{i1},...,a_{ip}],$$
$$g:\mathbf{R}\to\mathbf{R}^q,\ g(a_{i,j,k})=[a_{i,j,k1},...,a_{i,j,kq}], \tag{17}$$

and the extension can be generalized by adding extra indices after i, j and k. The *zero-step extension* of a signature is defined as the function

$$\begin{aligned}&{}^{g}\overline{@}^{p}:\mathrm{S}\to\mathrm{S},\\ &{}^{g}\overline{@}^{p}(a^{1,2,...,n})={}^{g}\overline{@}_1^{p}({}^{g}\overline{@}_2^{p}(...({}^{g}\overline{@}_n^{p}(a^{1,2,...,n}))))\\ &=a^{[1,...,p],[1,...,p],...,[1,...,p]},\end{aligned} \tag{18}$$

where

$$g:\mathbf{R}\to\mathbf{R}^p,\ g(a_j)=[a_{j1},...,a_{jp}],\ j=1...n. \tag{19}$$

Definition 5. The *pruning* of a signature is defined as one of the three functions

$$\begin{aligned}&\varnothing_i:\mathrm{S}\to\mathrm{S},\\ &\begin{cases}\varnothing_i(a^{1,2,...,i,...,n})=a^{1,2,...,i-1,i+1,...,n}, & \text{if } i\le n,\\ \varnothing_i(a^{...})=a^{...}, & \text{otherwise},\end{cases}\\ &\varnothing_i:\mathrm{S}\to\mathrm{S},\\ &\begin{cases}\varnothing_i(a^{1,...,[1,...,m]_i,...,n})=a^{1,...,i-1,i+1,...,n}, & \text{if } i\le n,\\ \varnothing_i(a^{...})=a^{...}, & \text{otherwise},\end{cases}\\ &\varnothing_{i,j,k}:\mathrm{S}\to\mathrm{S},\\ &\begin{cases}\varnothing_{i,j,k}(a^{1,...,[1,...,[1,...,[1,...,q]_k,...,...,r]_j,...,m]_i,...,n})\\ =a^{1,...,[1,...,[1,...,k-1,k+1,...,r]_j,...,m]_i,...,n}, & \text{if } i\le n,\ j\le m, k\le r,\\ \varnothing_{i,j,k}(a^{...})=a^{...}, & \text{otherwise}.\end{cases}\end{aligned} \tag{20}$$

This definition can be generalized as well by adding extra indices after i, j and k, where the notation for the pruning of a signature is

$$a^{...}\varnothing_i=b^{...}. \tag{21}$$

Definition 6. The *addition* of two signatures is defined as the function

$$\begin{aligned}&{}^{f}\oplus_i:\mathrm{S}\times\mathrm{S}\to\mathrm{S},\\ &{}^{f}\oplus_i(a^{1,2,...,[1,...,m]_i,...,n},b^{1,2,...,m})=c^{1,2,...,[1,...,m]_i,...,n},\end{aligned} \tag{22}$$

where

$$\begin{aligned}&c_k=a_k\ \ \forall\ k\ne i,\ c_{ij}=f(a_{ij},b_j)\ \ \forall\ j=1...m,\\ &f:\mathbf{R}^2\to\mathbf{R}.\end{aligned} \tag{23}$$

If

$$a^{1,2,...,n},\ b^{1,2,...,m}\in\mathrm{S} \tag{24}$$

then

$$\begin{cases}a^{1,2,...,n}\,{}^{f}\oplus_i b^{1,2,...,m}={}^{g}\overline{@}_i^{m}(a^{1,2,...,n})\,{}^{f}\oplus_i b^{1,2,...,m}\\ =c^{1,2,...,[1,2,...,m]_i,...,n}, & \text{if } i\le n,\\ a^{...}\,{}^{f}\oplus_i b^{...}=a^{...}, & \text{otherwise},\end{cases} \tag{25}$$

where

$$\begin{aligned}&c_{ij}=f(a_{ij},b_j),\ [a_{i1},...,a_{im}]=g(a_i),\ j=1...m,\\ &c_k=a_k\ \forall\ k\ne i.\end{aligned} \tag{26}$$

This definition can also be generalized by adding extra indices after i, where the notation for the addition of two signatures is

$$a^{...}\,{}^{f}\oplus_i b^{...}=c^{...}. \tag{27}$$

These operators, namely contraction, extension, pruning and addition and the other ones defined in [1], can manipulate signature trees as well. The only difference between manipulations concerning signatures and signatures trees concerns the fact that data transformation do not exist in case of signature trees.

IV. Application Dedicated to Fuzzy Inference System Modeling

Using the signatures, the classes and signatures, the operators on signatures and the examples illustrated in [1] and [6], we use the fuzzy inference system design presented in [1] and we next develop this system by a new application presented in this section. The idea is to obtain the structure of the proto fuzzy inference system and to particularize it, by pruning, into a specific fuzzy inference system.

The *proto fuzzy inference system* is defined in [1] as the fuzzy inference system which contains all possible rule bases relative to the fuzzy sets

$$AI_{i,1,...,k_i}\ \text{ and }\ AO_{j,1,...,s_j}. \tag{28}$$

The following notation is used for the proto fuzzy inference system:

$$\{I_{1,...,n},F_{k_1,...,k_n},O_{1,...,m}\}, \tag{29}$$

where $AI_{i,1,...,k_i}$ are the fuzzy sets defined for the inputs $I_i,\ i=1...n$, $\mu I_{i,1,...,k_i}$ are the membership functions corresponding to the fuzzy sets defined for the inputs $I_i,\ i=1...n$, XI_i are the universes of discourse of the inputs $I_i,\ i=1...n$, and $|XI_i|=k_i$ is the cardinal of the set XI_i, $F_{k_1,...,k_n}$ is the fuzzy state table, $AO_{j,1,...,s_j}$ are the fuzzy sets defined for the outputs $O_j,\ j=1...m$, $\mu O_{j,1,...,s_j}$ are the membership functions corresponding to the fuzzy sets defined for the outputs O_j, $j=1...m$, XO_j are the universes of discourse of the outputs O_j, $j=1...m$, and $|XO_j|=s_j$:

$$\begin{aligned} AI_{i,1,\dots,k_i} &= \{(x_i, \mu I_{i,1,\dots,k_i}(x_i)) \mid x_i \in XI_i\}, \\ AO_{j,1,\dots,s_j} &= \{(y_j, \mu O_{j,1,\dots,s_j}(y_j)) \mid y_j \in XO_j\}. \end{aligned} \tag{30}$$

The signature tree associated to the proto fuzzy inference system (29) can be computed in terms of

$$\begin{aligned} \hat{a}^{\cdots} = ((((\hat{a}^{1,\dots,m} \oplus_1 \hat{a}^{1,\dots,s_1}) \oplus_2 \hat{a}^{1,\dots,s_2}) \dots \oplus_m \hat{a}^{1,\dots,s_m}) \\ \otimes \hat{a}^{1,\dots,nF}) \otimes \hat{a}^{1,\dots,n}, \end{aligned} \tag{31}$$

where $\hat{a}^{1,\dots,m}$ is the signature tree of the output, $\hat{a}^{1,\dots,n}$ is the signature tree of the input, $\hat{a}^{1,\dots,s_j}$, $j=1...m$, is the signature tree of the output fuzzy sets, and $\hat{a}^{1,\dots,nF}$ is the signature tree of the fuzzy states table.

We will apply these results to the system presented in Fig. 1. Fig. 1 illustrates a two inputs-single output system, which can be viewed as a particular case of PI-fuzzy controllers [29], [49], [68], [69], developed by incorporating the knowledge from PI controllers [48], [50]. For our purpose the important information concerning the system illustrated in Fig. 1 is its structure.

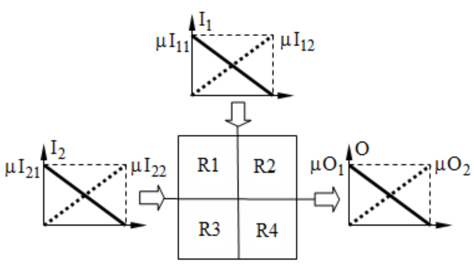

Fig. 1. Structure of fuzzy inference system.

Each input has two membership functions, μI_{11} and μI_{12} for I_1, and μI_{21} and μI_{22} for I_2, The output O has two membership functions, μO_1 and μO_2. Using all possible combinations of inputs we have obtained a fuzzy states table which consists of the rules R1, R2, R3 and R4. Using (31), the formula for the proto fuzzy inference system is

$$\hat{a}^{\cdots} = (\hat{O}^{1,2} \otimes \hat{R}^{1,\dots,4}) \otimes \hat{I}^{1,2}. \tag{32}$$

This will give the structure represented in Fig. 2 (a). Several particular solutions can be derived by pruning the proto fuzzy inference systems. Two examples of such particular solutions are

$$\hat{a}_1^{\cdots} = \varnothing_{2(1,2)}(\varnothing_{1,(3,4)}(\hat{a}^{\cdots})) \tag{33}$$

and

$$\hat{a}_2^{\cdots} = \varnothing_{2(1,2,4)}(\varnothing_{1,(3)}(\hat{a}^{\cdots})). \tag{34}$$

These two examples are illustrated in Fig. 2 (b) and (c).

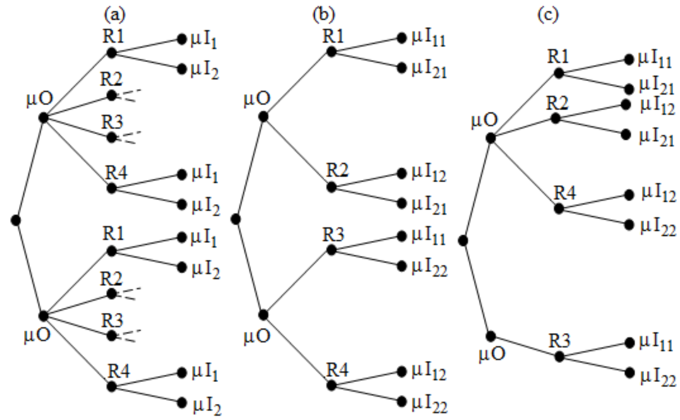

Fig. 2. Proto fuzzy inference system (a) and two examples expressed in (33) $\hat{a}_1^{\cdots}$ (b) and in (34) $\hat{a}_2^{\cdots}$ (c).

V. Conclusion

This paper has suggested directions to use signatures in order to develop modeling and design of AI applications. An application concerning the modeling of fuzzy inference systems has been offered.

The main limitation of our results is that we have given an initial research result which is not yet organized in a systematic and complete manner. Future research will offer answers to the two mentioned AI paradigms, i.e., cognition and embodiment, by the development of signatures for both. Illustrative modeling applications will be targeted using examples inspired from [9] and [70]–[75] including deterministic expert systems.

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