HYCONES II: a tool to build Hybrid Connectionist Expert Systems

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This paper describes HYCONES II - a tool to enable the construction of hybrid connectionist expert systems to solve classification problems. HYCONES II offers to the knowledge engineer a hybrid knowledge base that integrates frames with three different neural network models: the combinatorial neural model - CNM, the Fuzzy ARTMAP and the Semantic ART - SMART models. The latter is a new model, introduced by this paper, based on a combination of the two previous models. The validation section compares the performance of these three neural models to solve diagnostic problems in two medical domains. This paper also presents HYCONES II knowledge representation features, built in the symbolic component of its hybrid knowledge-base, to deal and represent fuzzy medical variables. Finally, the present status and future developments of the project are presented.

INTRODUCTION

Hybrid connectionist expert systems solve well-known problems of conventional expert systems, such as knowledge acquisition and learning. Although this is still a new technology, hybrid systems are being successfully used in several application areas [1]. HYCONES first version integrated frames with the combinatorial neural model - CNM [2]. The system showed a good performance: 31 out of 33 congenital heart disease diagnoses were correctly pointed out by HYCONES, when using its hybrid knowledge base (HKB) automatically trained from scratch, using a case database [3]. Because of this promising results, it was decided to progress to HYCONES II - a tool to build hybrid systems, offering to the knowledge engineer options to choose different neural models to work with and features to facilitate domain knowledge representation when dealing with fuzzy variables.

This paper gives an overview of HYCONES II, comparing the performance of the different neural networks models now available, when solving diagnostic problems in two different domain areas in medicine.

THE FUZZY ARTMAP MODEL

The Adaptive Resonance Theory (ART) deals with a system involving self-stabilizing input patterns into recognition categories, while maintaining a balance between the properties of plasticity and stability. ART models are being successfully used to recognize characters [4]. ART includes a series of different connectionist models: Fuzzy ARTMAP, Fuzzy ART, ART 1, ART 2, and ART 3. Among them, the Fuzzy ARTMAP one stands out for being capable of learning analogical patterns, using two basic ART modules. The Simplified Fuzzy ARTMAP model is a simplification of the Fuzzy ARTMAP neural network. Contrasting with the first model, the new one is capable of learning analogical patterns using only one ART module. A description of this model can be found in [5]. The presence of a single ART module does not hamper the Simplified Fuzzy ARTMAP model. The same performance levels are attained when the latter one runs without the second ART module. This is certified by the match-tracking strategy, that jointly maximizes generalization and minimizes predictive error.

Due to the powerful features of recognizing categories inherent to the ART model, it was decided to incorporate it in HYCONES II and validate its performance to solve medical diagnostic problems, comparing it to the CNM version of HYCONES. The goal was to offer more options to the knowledge engineer. As it will be described below, the Fuzzy ARTMAP model, although reported as excellent to recognize categories, concluded as much as CNM for the right diagnoses, but the semantic content of the activated neural networks was inadequate to be used in the explanatory module of HYCONES. This lack of semantics was investigated and, finally, a new neural model was proposed - the Semantic ART - SMART. The next sections describe how this was accomplished.

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HYCONES' II ARCHITECTURE

HYCONES II keeps the basic architecture of its prior version, adding the other two neural networks (NN) models: Fuzzy ARTMAP and Semantic ART (SMART) and their respective learning algorithms: **(1) the Hybrid Knowledge Base (HKB)** - consisting of a combination of a frames mechanism with the three NN models: CNM, Simplified Fuzzy ARTMAP and Semantic ART (SMART); **(2) the Inference Machine** - controlling the inference process through the activation of the NN. Whenever the evidence is not enough for the NN to reach a conclusion, the inference process carries on with the pattern-matching mechanism in the symbolic part of the knowledge-base; **(3) the Learning Machine** - responsible for: the inductive and deductive learning features of the CNM algorithm; the Fuzzy ARTMAP algorithm and, finally, the SMART learning algorithm that is an adaptation of the CNM method; **(4) the Case Database** - responsible for the storage of all correctly solved classification problems. These correct classifications are used by the learning machine as the training examples for the HKB refinement. A description of HYCONES' architecture, its integration between frames and NN and the CNM learning algorithm can be found in [2,6,7].

The first step in the development of HYCONES II was, then, the incorporation of the Fuzzy ARTMAP model in the connectionist component of the HKB. This implied in a complete modification of the learning process, as it was implemented for CNM. Learning in Fuzzy ARTMAP is based on the creation of recognition categories in response to an arbitrary order of input cases. This process is regulated by a vigilance parameter, which is a number in a range from zero to one. The vigilance parameter defines the networks' level of generalization and specialization. When the parameter is set to zero, the network assumes maximum generalization; when it is set to one, the network assumes maximum specialization.

VALIDATION

Two medical domains were chosen to validate HYCONES' II performance: congenital heart diseases (CHD) and renal syndromes. This domain selection was only due to the case database availability. To build up the CHD case base, 66 medical records were extracted from the cardiac surgery database of the Institute of Cardiology RS (ICFUC-RS). These records cover the period extending from January 1986 to December 1990 and describe 22 cases of *Atrial Septal Defect* (*ASD*), 29 of *Ventricular Septal Defect* (*VSD*), and 15 of *Atrial-Ventricular Septal Defect* (*AVSD*), the three most frequent congenital heart diseases. For validation purposes, 33 additional cases, from the same database and period mentioned above, were also extracted. From these cases, 13 report *ASD*, 10 mention *VSD* and 10 refer to *AVSD*. This database is exactly the same used to validate HYCONES' first version [3]. To build the renal syndromes case base, 381 medical records from the database of the *Paulista School of Medicine* were analyzed and 58 evidences were semi-automatically extracted, covering the patients' clinical history and physical examination data. From the total number of selected cases, there are 136 occurences of *Uremia*, 85 of *Nephritis*, 100 of *Hypertension*, and 60 of *Calculosis*. From the 381 cases analyzed, 245 were randomly chosen to build the training set, while the remaining ones were used to build the testing set.

To validate HYCONES II, 46 versions of the HKB with congenital heart diseases were built; for the renal domain, another set of 46 HKB versions were constructed. For both medical domains, the HKBs were automatically generated from the training databases. From these 46 versions, one operates with the CNM model and the other 45 deal with the two ART models. These ART versions are divided in three groups: 15 versions were built using the Simplified Fuzzy ARTMAP model; 15 used the Simplified Fuzzy ARTMAP model without the normalization of the input patterns, and 15 used the Semantic ART model (described below). These 45 ART versions were grouped in three sets of five, according to the vigilance parameter used: 0.0; 0.7; and 0.9. Like other ART architecture, Fuzzy ARTMAP performance depends on the order of the input cases. For this reason, the cases were given in five different random orders, originating five different HKB versions for each distinct value of the vigilance parameter. Therefore, fifteen distinct versions of the trained HKB were created. For validation purposes, these fifteen versions were grouped into three sets, according to their correspondent vigilance, named **ART0, ART7** and **ART9,** respectively. The results shown in TABLE I below compare the CNM version with the best result obtained with Simplified Fuzzy ARTMAP model for both medical domains.

TABLE I - HYCONES II FUZZY ARTMAP VALIDATION

Diagn	CNM CHD N (%)	ART7 CHD N (%)	CNM Renal N (%)	ART7(*) Renal N (%)
Correct	31 93.9	29 87.9	95 74.8	108 85.0
Wrong	0 -	4 12.1	10 7.9	19 15.0
Not enough evidence	2 6.1	0 -	22 17.3	0 -
Total	33 100	33 100	127 100	127 100

(*) $p<0.05$ under the $\chi 2$ test, when compared to the CNM version.

HYCONES II - Simplified Fuzzy ARTMAP and HYCONES - CNM similarly performed for the CHD domain. The first one pointed out correctly to 29 of the 33 testing cases (87.9%), while the second one indicated correctly 31 of the same cases (93.9%). In the renal syndromes domain, however, the performance of HYCONES II - Simplified Fuzzy ARTMAP was superior to the one exhibited by CNM ($p < 0.05$). Both versions pointed out correctly, respectively, to 108 (85%) and 95 (74.8%) diagnoses of the 127 testing cases presented to the system.

HYCONES II - Simplified Fuzzy ARTMAP, therefore, displayed a satisfactory performance. However, the semantic contents of the neural nets it generated made no medical sense and could not be used to explain the system reasoning. Also, these contents were completely different from the ones stemming from the CNM networks, which were very similar to the knowledge graphs elicited from experts in CHD. In fact, the Simplified Fuzzy ARTMAP version used evidence that represented the complementary coding of the input pattern, to reach a diagnosis. This coding, inherent to the Simplified Fuzzy ARTMAP model, duplicates the input pattern, generating a new one depicting the evidence observed (*on-cell*) and, at the same time, the absent evidence, in relation to the total evidence employed to represent the input cases (*off-cell*).

The next step taken was to improve the semantic contents of the Simplified Fuzzy ARTMAP model. To achieve this, the complementary coding process was removed and the modified model was, then, revalidated through the same testing sets as above described. In the CHD domain, the performance of HYCONES II - Simplified Fuzzy ARTMAP, without complementary coding, proved to be inferior to the one presented by CNM ($p < 0.05$). In the renal syndromes domain, the performances of HYCONES II - Simplified Fuzzy ARTMAP, without complementary coding, and HYCONES - CNM were similar. The first pointed out correctly to 98 of the 127 testing cases (77.2%), while the second one pointed out correctly to 95 of the same cases (74.8%).

However, the recognition categories formed by this modified Simplified Fuzzy ARTMAP still presented quantitative and qualitative differences in their contents, when compared to the networks activated by CNM and to the knowledge graphs elicited from experts. This discrepancy, although smaller than the one observed in the original Fuzzy ARTMAP model, still restrained HYCONES' explanation mechanism.

THE SEMANTIC ART MODEL

The Semantic ART model (SMART) was, then, proposed. Its goal was to improve the semantic contents of ART recognition categories. To build this new model, the Simplified Fuzzy ARTMAP architecture was preserved, while its learning algorithm was replaced by the CNM inductive learning mechanism (the punishments and rewards algorithm, associated with the pruning mechanism) [8]. A new validation phase was, then, performed over the same testing sets, as depicted in TABLE II.

TABLE II - HYCONES II SMART VALIDATION

Diagn	CNM CHD N (%)	SMART CHD N (%)	CNM Renal N (%)	SMART Renal (*) N (%)
Correct	31 93.9	29 87.9	95 74.8	108 85.0
Wrong	0 -	4 12.1	10 7.9	19 15.0
Not enough evidence	2 6.1	0 -	22 17.3	0 -
Total	33 100	33 100	127 100	127 100

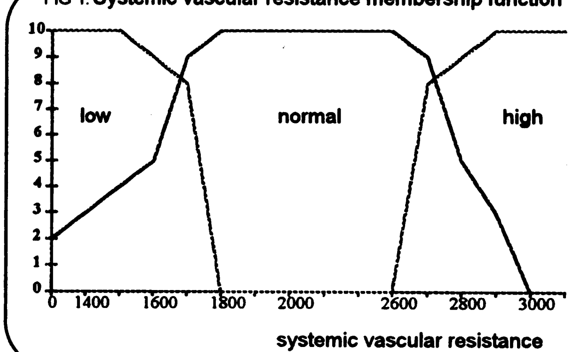
(*) $p<0.05$ under the $\chi 2$ test, when compared to the CNM version.

For the CHD domain, the performance comparison among SMART and CNM versions showed similar results. The first one pointed out correctly to 29 of the 33 testing cases (87.9%), while the second one singled out correctly 31 of the same testing cases (93.9%).
For the renal syndromes domain, the performance of HYCONES II - SMART was superior to the one presented by the CNM version ($p < 0.05$), and equal to the performance presented by the Simplified Fuzzy ARTMAP version. SMART and Simplified Fuzzy ARTMAP singled out correctly 108 of the 127 testing cases (85%), while the CNM version pointed out correctly 95 of the same 127 testing cases (74.8%).
Finally, it was observed that the NN generated by HYCONES II - SMART were similar in content to the networks generated by CNM and to the knowledge graphs elicited from multiple experts.

DEALING WITH FUZZINESS

It is well known that humans can operate with and decide upon fuzzy or uncertain data. Usually, to describe what is observed in the real world, human beings create categories to qualify the real objects. For example, someone's height is usually described as tall, medium or small. The fuzzy sets theory deals with that through the definition of membership functions in fuzzy spaces. These functions take each individual domain value and figure out the respective membership possibilities in each fuzzy space. In this example the fuzzy spaces are: tall, medium and small and the domain value is the individual height measurement. To build HYCONES II application to support the treatment of patients submitted to cardiac surgery, a case database was used and an expert was interviewed, invoking a knowledge acquisition methodology based on knowledge graphs [9]. Very frequently, the expert came up with graphs that used categories to qualify the medical finding. For example, it was mentioned by him that the hemodynamic parameter cardiac output is categorized as *adequate, inadequate or marginal*. The same approach was used to describe other hemodynamic parameters or lab data. As the knowledge acquisition phase proceeded, it became clear that the expert, whenever dealing with quantitative data, instead of reasoning upon the raw data, used categories or linguistic variables that defined fuzzy spaces, as they are named in the fuzzy sets theory. It became then evident that the concepts of the fuzzy sets theory were necessary to represent this knowledge in HYCONES II HKB. The next step was to ask the expert to submit the information about the compatibility (membership) functions used to define the semantics of the linguistic variables. As this line of questioning had never been tried before with the expert, there was, initially, the belief that he would find it difficult to explicit this knowledge. Surprisingly, he defined these functions very easily and promptly, either as a graphic or a table. Even though most of the time he drew a trapezoid function, in some cases the morphology of the pertinence function was unusual, as shown in FIG 1, where the finding systemic vascular resistance is described as: *low*, *normal* and *high*.

FIG 1. Systemic vascular resistance membership function



To represent these fuzzy variables in the symbolic component of HYCONES II HKB, the domain knowledge was divided into two sub-classes: one representing those findings where linguistic variables had been used (*fuzzy_findings*) and another to describe *non-fuzzy* ones (*non_fuzzy_findings*). In addition, an object to describe the linguistic variables was created - *language_var*. A semantic link connects these two objects. A simple and direct method to figure out the value of the membership functions was implemented. Whenever a case is being entered, either in the creation of the case database or in the consultation mode, HYCONES II verifies if the given finding is a fuzzy one. If so, instead of giving to the inference process (NN) the raw data, a transformation is made, in order to offer to the NN a finding described by its corresponding linguistic variables, together with the values of the membership function that the raw data can be mapped into.

In addition to the system intended to support post-operative treatment of cardiac surgery patients, HYCONES II fuzzy features are also being used in the development of the *Pharmacy* system. This system is intended to support the hospital pharmacist. It will be integrated in the hospital information system to check the medical prescription, issuing warnings whenever necessary.

CONCLUSION

There are several contributions to single out in this paper: the design, implementation and validation of the Simplified Fuzzy ARTMAP and SMART models. The latter one, however, stands out for its learning mechanism, which provides a higher semantic value to the recognition categories, when compared to the categories formed by conventional ART models. This important enhancement is obtained through the incorporation of specificity and relevance concepts to ART's dynamics. The original ART algorithm mainly considers the frequency of occurrence of the given evidence to create its recognition categories. Sensitivity is, however, only one of the factors considered by experts. Previous work has already shown that experts are able to identify not only what is more frequent, but rather, what is more relevant and specific while solving a diagnostic problem [9]. CNM's learning algorithm intends to imitate this behavior. CNM dynamics allows for a smooth learning curve, leading to an almost *intuitive* recognition of environmental patterns. By rewarding those pathways showing higher frequency and specificity, and punishing those less frequent, CNM algorithm guarantees the identification of the essential features of each category. Fuzzy ARTMAP's performance was increased when the CNM learning algorithm was incorporated into its dynamics and, what is more important, the newly created recognition categories presented a semantic content similar to knowledge graphs elicited from experts and also similar to CNM's trained networks.

HYCONES II, thus, offers to the knowledge engineer the choice among three different neural networks: CNM, Semantic ART and Simplified Fuzzy ARTMAP, all of which display good performance. Indeed, the first and second models, contrasting with the third one, support the context in a semantic way. In addition to the new neural models, HYCONES II is now able to describe and represent fuzzy medical findings.

Finally, this paper describes an additional contribution of an on-going research project on Artificial Intelligence in Medicine, led by the Medical Informatics Group of the Institute of Cardiology RS Medicine Graduate Program, in cooperation with the Federal University of Rio Grande do Sul Graduate Program in Computer Science. This research effort already led to two M.Sc. dissertations and some additional publications [3,5,7,8,10]. Presently, other two M.Sc. dissertations are invoking HYCONES II.

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