Neuro-Symbolic Hybrid Systems for Industry 4.0: A Systematic Mapping Study

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Abstract. Neuro-symbolic hybrid systems (NSHS) have been used in several research areas to obtain powerful intelligent systems. A systematic mapping study was conducted, searching studies published from January 2011 to May 2018 in three author databases defining four research questions and three search strings. With the results a literature review was made to generate a map with main trends and contributions about the use of NSHS in Industry 4.0. An evaluation rubric based on the work of Petersen et al. (2015) was applied too. In a first exploratory search 544 papers was found, but only 330 had relation with research theme. After this first classification a second filter was applied to identify repeated articles or which had not relevance for solve the research questions, obtaining 118. Finally, 50 primary studies was selected. This paper is a guide aimed at researching and obtaining evidence on the shortage of publications and contributions about the use of neuro symbolic hybrid systems applied in Industry 4.0 environment.

Keywords: Neuro-symbolic hybrid system (NSHS) · Industry 4.0 · Artificial intelligence · Systematic mapping study

1 Introduction

A hybrid system of artificial intelligence is defined as several intelligent subsystems integrated and that collaborate and influence among them. A particular class of these systems are the *neuro-symbolic hybrid systems* (NSHS) defined in [1] as systems based primarily on artificial neural networks that allow a symbolic interpretation or an interaction with symbolic components. The main properties of NSHS are as follows: efficiency of global system, components with a strong fusion, global learning and complementarity between symbolic and numeric knowledge [2]. Sahin et al. (2012) offer an important literature review about hybrid systems and their trends, algorithms and areas where these systems are gaining interest [3]. The authors mention in their research the important number of new industrial applications developed using hybrid systems. In an exploratory search only one systematic mapping study about Industry 4.0 was found, but it had not any relationship with neuro-symbolic hybrid systems.

According to Wortmann et al. (2017) a systematic mapping study is the search and classifies of primary studies about an investigation area [4]. For this systematic

L. Uden et al. (Eds.): KMO 2019, CCIS 1027, pp. 455–465, 2019.
https://doi.org/10.1007/978-3-030-21451-7_39

mapping study, authors apply the guidelines, useful practices and suggestions established by Kitchenham, Petersen and others [4–10]. Therefore, the advantages described by the previously authors about systematic mapping studies have motivated the development of this with the aim of identifying trends in the application of hybrid systems in Industry 4.0. In computer sciences the first mapping studies developed were focused on software engineering and their authors recommended it for research areas with a few important and relevant primary studies [5, 6]. After the introduction, Sect. 2 presents a background about Neuro-Symbolic Hybrid Systems. The rest of the paper is structured as follows: the research method is described in Sect. 3; the results are summarized in Sect. 4 and finally conclusions are presented in Sect. 5.

2 Background

In this section an overview about the Neuro - symbolic hybrid systems and Industry 4.0 are making as previous point in the developing of our mapping study. Hybrid systems arise from the symbiosis of various artificial intelligence (AI) techniques such as: agents, neural computing, automatic learning, fuzzy logic, evolutionary algorithms [2, 11]. During the nineties a boom began in the implementation of hybrid systems for their ability to solve complex problems of a real environment [12]. To date, hybrid artificial intelligence systems, also identified as HAIS, are a multidisciplinary field of research that continues to expand [13]. Before introduce the Neuro-Symbolic Hybrid System's concept is necessary to talk about two approaches: (i) the connectionist (artificial neural networks) and (ii) the symbolic (rules, trees and others), both has been used by independent form with the aim to demonstrate which is the best to solve the problems. After the researches find that weaknesses of some of them can be integrated with the strengths of the other; such as: the difficulty of artificial neural networks to explain the results and the difficulty of symbolic approach to generalize knowledge, are integrated and complement each other in a single approach, as a consequence the Neuro-Symbolic Hybrid System emerges. Neuro- Symbolic Hybrid System uses the artificial neural networks algorithms as the principal option to solve the problems [14–16].

Industry 4.0 is a new term using to define an emerging organization concept in which there is a technological control over the life cycle of production and the entire value chain [17]. Industry 4.0 is an emerging structure established by the German Federal Government in which manufacturing and logistics systems make a match between a great volume of data, information, production and business processes by means of Cyber Physical Systems [17–21]. For Lee et al. [19] the principal objective of Industry 4.0 is the need to convert regular machines to self-aware-learning machines in order to improve their overall performance and maintenance process.

3 Research Method

A systematic mapping study is a secondary study based on the search for existing scientific evidences on a topic and then provide indication of the quantity of them. The benefits of a systematic mapping study are indicated as follows [22]:

- Identify groups of papers based on a specific theme through a systematic and objective procedure.
- Systematic mapping study helps to propose new researches in the analyzed field.
- A previous Mapping study facilitates futures systematic literature reviews (SLR) which aim resolve specific research issues.

In computer science, the guidelines, procedures and rubrics to develop a systematic mapping studies has been making in general by the software engineering community and are defined in [5, 6, 23, 24]. Therefore, the research method is organized in three stages: (1) Protocol definition and establishment of research questions; (2) Definition of search strategies and description of inclusion and exclusion criteria; (3) Selection of relevant publications.

3.1 Research Questions

With the aim to identify important researches about Neuro-Symbolic Hybrid Systems for Industry 4.0, the following research questions are proposed:

- **Q1**: What researches and contributions have been made regarding neuro-symbolic hybrid systems (NSHS) for Industry 4.0?
- **Q2:** What challenges in the Industry 4.0 context can be addressed through the application of NSHS?
- **Q3:** What predictive models with sensor network data have been designed from the integration of NSHS?
- **Q4:** In which environments have the found prediction models been applied?

3.2 Search Strategy

Finding relevant publications that possibly respond to the research questions we have asked requires designing appropriate search clauses and selecting the most relevant scientific libraries. For this research, the following repositories will be used: Web of Science, Scopus and IEEE Digital Library. In a scientific systematic mapping study a good practice is construct the search strings using a defined approach. In this case, authors use the PICO approach, suggested by [6, 9] in which: **P** is the Population that applied to this study which corresponds to Neuro Symbolic Hybrid Systems; **I** is the Interventions authors paper Intervention; **C** is the Comparison of found studies and finally **O** is the Outcome or study results. PICO helps authors to define the keywords and search strings and determine if it is necessary to use synonyms.

The search strings were defined to perform searches using exact words to avoid articles that not contain relevant information about the neuro-symbolic hybrid systems applied to industry or industry 4.0. For this reason, the search strings are enclosed in quotes (e.g., “Industry 4.0”) to extend the obtained results. In Table 1, the search strings used in searches are described and identified with an ID. For example, the first search string is identified with B1 and next search strings also use an ID.

This research contemplates establishing criteria for the inclusion or exclusion of valid articles for the development of a systematic mapping study of the literature. In the following section the applied criteria are described.

Table 1. Search strings.

ID	Description
B1	"Industry 4.0" AND "systematic literature review" OR "literature review" OR "overview" OR "survey" OR "systematic mapping study"
B2	Neuro-symbolic hybrid system OR hybrid neuro-symbolic system OR hybrid expert system AND Industry
B3	Neuro-symbolic hybrid system OR hybrid neuro-symbolic system OR hybrid expert system AND Industry 4.0

3.3 Inclusion and Exclusion Criteria

Inclusion/Exclusion criteria are used to obtain only relevant papers to answer the research questions [5, 6]. Therefore, to select studies, the authors established inclusion/exclusion criteria as follows:

- Inclusion criteria:
  - Studies published in journals, conferences and workshops with peer revision whose title, abstract and keywords correspond with the search strings defined in Table 1.
- Exclusion criteria:
  - Papers that only mention the terms but they do not have an important contribution to the research theme.
  - Authors decide exclusion of all papers published in journals or conferences which do not have peer revision.
  - Papers duplicated in the repositories mentioned previously in this document and used to make the search.

3.4 Classification and Evaluation

To obtain the final publications with which the map was designed, a systematic classification process is defined by means of a stepwise scheme. Firstly, an exploratory search is carried out. In the second stage the authors identify the duplicated articles in the repositories and they will be eliminated to begin with the third stage, which is the revision of each one in search of relevant concepts for the research. In first exploratory search 544 papers was found but only 330 had relation with research theme. After this first classification a second filter was applied to identify repeated articles or which had not relevance for solve the research questions. A total of 330 relevant documents were found during the search, from which 118 were selected and 212 were excluded.

In this paper the Petersen's rubric presented in [6] was used. The rubric describes 26 actions to evaluate the quality of a systematic mapping study (SMS). One of the advantages of this rubric is that it can be used by readers to quickly evaluate the action applied in an SMS. In this sense, to determine the quality of an SMS, Petersen establishes an average of 33%. Therefore, the higher the percentage of actions taken, the better the quality of the study [22]. Figure 1 shows a total of 26 actions from the list defined by [6, 22], from which 15 were taken, which means a 57.69% of average and quality of mapping study presented in this paper.

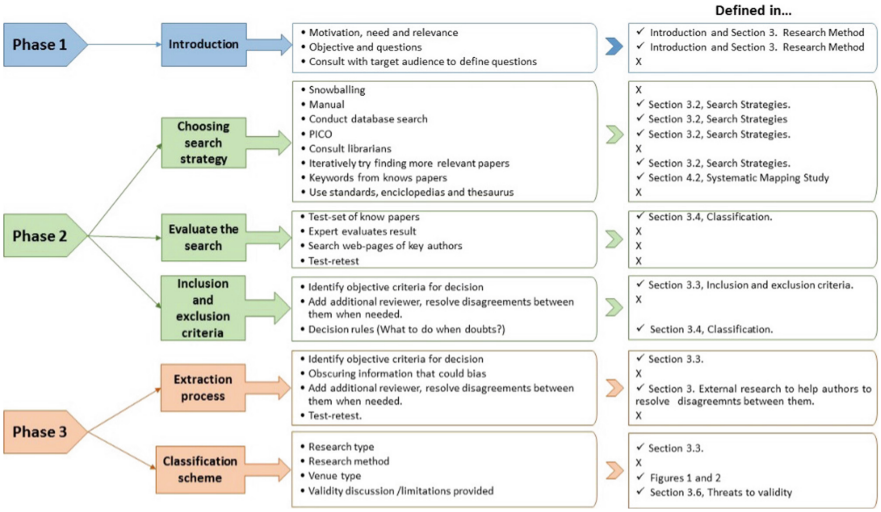

Fig. 1. Action conducted in this study: (✓) taken and not taken (×)

4 Results

In this section, after reading and analyzing each article in order to find the meaningful terms, the authors present: (i) clouds with the relevant keywords found in articles; (ii) tables with selected journals and conference papers and (iii) the answer to the initial research questions described in Sect. 3.1 of this document. Figure 2 shows the result obtained with the word cloud technique to extract the most representative terms from the articles by search string (B1, B2, and B3): (a) journal and (b) conference. Table 2 summarizes journal and conference papers that were selected papers by each search string. All of them are included in the reference section.

4.1 Answers to Research Questions

- **Q1: What research and contributions have been made in relation to neuro-symbolic hybrid systems for Industry 4.0?** After the mapping study, authors identify some papers related with neuro-symbolic approach, but principally with hybrid expert systems. Using Industry 4.0 in the search string, only one relevant paper was found: *"A hybrid expert decision support system based on artificial neural networks in process control of plaster production - An Industry 4.0 perspective"* in which their authors present a Hybrid Expert Decision Support System (EDSS) model, which integrates Neural Network (NN) and Expert System (ES) to detect unnatural CCPs and to estimate the corresponding parameters and starting point for the detected CCP [1]. The other papers propose the use of the following approaches:
  - Hybrid expert systems or expert systems: [40, 48, 73, 74]
  - Hybrid intelligent systems [49, 75]
  - Neuro-rules and neuro-symbolic approach [54–56]

The Question 1 (Q1) is important because authors found only a few relevant papers that used "neuro-symbolic hybrid systems applying to Industry 4.0".

Table 2. Selected journal and conferences papers

ID	Journal	Conference
B1	[25–39]	[4, 61–71]
B2	[40–53]	[1]
B3	[3, 54–60]	[72]

- **Q2: What challenges in the Industry 4.0 context can be addressed through the application of NSHS?** Fault diagnosis, prediction, detect unnatural behaviors are some of the principal challenges in Industry that researchers are working during last years to solve through neuro-symbolic approaches, neural rules, neural networks or hybrid systems. Some of their results are described in [1, 40, 48, 49, 54–56, 59, 73–75].
- **Q3: What predictive models with sensor network data have been designed from the integration of NSHS?** In this research, authors have identified some relevant papers with predictive model but using hybrid systems such as:
  - Karelovic et al. (2015) present a framework for modeling and representation of hybrid systems, and the design and development of hybrid predictive controllers [48].
  - Kim et al. (2017) develop a hybrid expert system to failure diagnosis and prediction for an automatic preventive maintenance system [74].
- **Q4: To which environments have the prediction models found been applied?** The prediction models found have been applied on: (i) mineral processing [48] (ii) steelworks industry [74]; and (iii) plaster production industry [1]. This means that the design of prediction models through the use of hybrid systems is an optimal area for the development of future research.

Fig. 2. (a) Cloud of the keywords found in articles classified by search ID B1. (b) Cloud of the keywords found in articles classified by search ID B2–B3.

5 Conclusions

Neuro-symbolic hybrid system are not a new concept, since 90's decade, the researches in this field began with the objective to develop systems and build mechanisms more powerful with less efforts, necessary to generate an only intelligent system. Hybrid systems with artificial intelligence techniques such as Genetic Algorithm (GA) and Artificial Neural Networks (ANN) have been used by researchers to find solutions to complex problems. The mapping study presented in this paper had the aim to demonstrate the hybrid systems advantages to achieve important solutions in predictive models for fault diagnosis and other Industry 4.0 challenges.

From the synergy in the application of artificial intelligence approaches, symbolic systems that are based on the conjunction of fuzzy systems, neural networks, expert knowledge, genetic algorithms or automatic learning arise. These new approaches of neuro-symbolic hybrid systems have a remarkable theoretical growth and potential to solve complex industrial problems. Using neural networks, genetic programming or machine learning algorithms it is possible to generate solutions or design models with good generalist capacity in a real industrial environment. The neuro-symbolic hybrid approach has progressively taken strength and being used for the development of large and complex systems. Therefore, authors propose as future work the application and use of neuro-symbolic hybrid systems in Industry 4.0.

Acknowledgments. This work has been supported by project IOTEC: "Development of Technological Capacities around the Industrial Application of Internet of Things (IoT)". 0123-IOTEC-3-E. Project financed with FEDER funds, Interreg Spain-Portugal (PocTep). Inés Sittón-Candanedo has been supported by IFARHU – SENACYT scholarship program (Government of Panama).

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