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Neural networks: An overview of early research, current frameworks and new challenges

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ABSTRACT

This paper presents a comprehensive overview of modelling, simulation and implementation of neural networks, taking into account that two aims have emerged in this area: the improvement of our understanding of the behaviour of the nervous system and the need to find inspiration from it to build systems with the advantages provided by nature to perform certain relevant tasks. The development and evolution of different topics related to neural networks is described (simulators, implementations, and real-world applications) showing that the field has acquired maturity and consolidation, proven by its competitiveness in solving real-world problems. The paper also shows how, over time, artificial neural networks have contributed to fundamental concepts at the birth and development of other disciplines such as Computational Neuroscience, Neuro-engineering, Computational Intelligence and Machine Learning. A better understanding of the human brain is considered one of the challenges of this century, and to achieve it, as this paper goes on to describe, several important national and multinational projects and initiatives are marking the way to follow in neural-network research.

1. Introduction and goals of neural-network research

Generally speaking, the development of artificial neural networks or models of neural networks arose from a double objective: firstly, to better understand the nervous system and secondly, to try to construct information processing systems inspired by natural, biological functions and thus gain the advantages of these systems. Although currently computers are capable of carrying out some tasks more efficiently than the human brain, computers are not capable of equalling the brain's cognitive capacity, its flexibility, robustness and energy efficiency.

From the system engineering point of view a neural network is considered as a "**black-box**" as it imitates a behaviour rather than a structure and can reproduce any function; however studying the structure of the network does not provide any useful information about the system being modelled [1]. The physical organisation of the original system is not considered; instead a very flexible neural structure with a proven problem solving quality is used where problems of a similar nature are concerned. An advantage of the neural network is that it behaves as a non-linear black box, modelling and describing virtually any non-linear dynamics. As far as conventional statistics are concerned, the neural network may be considered as a non-identifiable model in the sense that various networks with varying topologies and parameters may be obtained which produce the same results.

Many of the topics thought up in the field of artificial neural networks, after a long and effective youth, have now acquired maturity and consolidation. They have proven to be very competitive in the resolution of real-world problems compared to more traditional data-analysis methods, usually based on explicit statistical modelling.

The concept of neural networks germinated independently but over time new contexts and disciplines have arisen, covering wider objectives which naturally include neural networks. In fact, artificial neural-network techniques combine naturally with others forming a set of computational procedures with a solid theoretical base, and with an unquestionable efficiency in the resolution of real problems in various fields of information processing. As a result, nowadays artificial neural networks are no longer considered as a self-contained field of research, rather they have become an integral part of new contexts and disciplines, among which we can find Computational Neuroscience, Neromorphic Computing, Neuroengineering, Natural Computation, Computational Intelligence, Soft Computing, Machine Learning and Neuroinformatics that will also be briefly considered in this paper.

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In recent years, government authorities in Europe and the USA have approved long term initiatives for the study of the human brain and have dedicated considerable economic resources to this end. Artificial neural networks, in various forms and at different levels, have been included in these research projects and the announcements of the projects have clearly set out the main challenges to be overcome in this field in the coming years.

Artificial neural systems for information processing constitute an inter-disciplinary subject, given that both neuroscientists and psychologists will benefit from the incorporation of methods and quantitative techniques allowing, via simulation, a greater in-depth knowledge of their field, whilst computer scientists and engineers will discover ideas inspired by biology, (such as learning models) allowing them to construct systems to satisfy the needs and challenges of the real world, and finally physicists and applied mathematicians will encounter new domains and challenges leading to advances in their fields. Currently, the computational models for artificial neural networks closest to biology ("bio-inspired" or "bio-mimetic") have a double objective:

1. *To carry out reverse engineering on the human brain;* that is to use computational models in the fields of neuroscience, cognitive science, and psychology to frame hypotheses that can be directly tested by biological or psychological experiments. The computer simulation of these models allows *in-virtual (in-silico)* experimentation, capable of predicting the behaviour of certain structures and functions and obtaining empirical results very close to those obtained from *in-vitro* or *in-vivo* experiments with biological samples. A greater knowledge of the structures and functions of the human brain is thus acquired without resorting to invasive methods to collect data or to carry out reflex-reaction tests. These techniques may even predict how different patterns of gene expression produce neurons with dissimilar morphologies identifying different molecules and diverse synaptic connections.
2. *To carry out artificial systems which attempt to imitate natural networks.* As we have already commented, modern computers are currently unable to equal the cognitive capacities, the flexibility, the robustness and the energy efficiency of the human brain. In fact, compared to computers, the brain works slowly (with spiking frequency signals of the order of hundreds of Hz) and with apparently low precision (stochastic individual neural processes). However, the whole brain carries out well organized computations in parallel (around 10^{16} synaptic operations per second), works in real time (in continuous interaction with the environment) with closed perception-action loops, and a very low energy consumption (approximately 30 W) beating the most powerful computers in certain "biologically relevant tasks", such as "manipulating objects", recognizing a scene after having viewed it once, etc. It also provides an elegant degradation of capabilities, self-repair, and modification through learning. These properties inspire scientists and engineers to search for new and disruptive computing models.

The origins of artificial neural networks were based on trying to mimic how the human brain performs a particular task via the use of simplified mathematical models. The basic concept consists of considering the brain as an information processing, highly complex, non-linear, parallel computer system. The most significant features of the domain are:

- The use of massive interconnection networks of simple processing units (neurons).
- Asynchronous parallel and distributed processing.
- Non-linear dynamics.
- Global interconnection of network elements.
- Self-organization.
- High-speed computational capability.
- Modification of the parameters of the network to carry out a specific task or adaptation to its environment via a **learning process**.

As will become evident in Section 2.3, artificial neural networks are being successfully applied in a wide range of areas and fields, contributing to the resolution of scientific and industrial real-world problems by performing specific tasks related to the capacity of inferring the underlying knowledge in observations and, in general, in conjunction with other information processing techniques or procedures.

These characteristics, as well as the general current state of the art and challenges for future research in the field of neural networks will be analysed in this paper. The text is organized in the following way: Section 2 analyses the concepts and the seminal research related to artificial neural networks that have arisen when models have been developed which aim to clarify human cognition and to build computer systems capable of resolving real-world problems. Section 3 focuses on describing the various frameworks and disciplines which artificial neural networks are currently integrated into and the role they play in each of these areas. Section 4 describes the main objectives and challenges of large governments with projects such as the Human Brain Project and the Brain Initiative, approved in recent years by government authorities of the European Commission and the USA, both of which are dedicating huge economic resources to this research, within which artificial neural networks appear in various forms. Section 5 presents our conclusions. Finally, we would like to point out that we have not tried to include exhaustive bibliographic references, citing every published contribution related to a specific topic, rather we have tried to provide support for our comments via some examples.

2. Topics related with ANNs

Various aspects of artificial neural networks may be considered from diverse points of view, such as: data problems, learning, models, structures and algorithms, simulators and hardware implementations, fields of use and real applications derived from biological inspiration.

Interest in artificial neural networks has evolved from their capacity to process information, which comes in data format. It is frequently necessary to carry out a pre-processing of the data before presenting it to the neural network. The main **data problems** which may occur are the following:

1. **Limited data for learning**. When only a limited amount of data is available cross-validation techniques are commonly used based on dividing the available data into two groups, one for learning and the other to validate the behaviour of the network. In order to gain a better knowledge of the network, the size and number of elements may be modified for training and evaluating the network in different situations [2,3].
2. **Imbalanced data**. A problem which occurs in learning, usually when in a classification problem there are many more elements of some classes than others [4]. There are several techniques to solve this problem, mainly focused either at the data level (sampling methods) or at the classifier level (modifying it internally). The sampling methods in imbalanced learning applications try to modify the imbalanced data set by some mechanisms in order to provide a balanced distribution by considering the representative proportions of class examples in the distribution. The cost-sensitive learning methods target the