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Neural Networks: Enhancing Smart Systems with Machine Learning

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Research Report

The present report approaches a way to improve smart systems. Through artificial intelligence applied in the mechanical engineering field, it provides a consistent algorithm that can reads data, trains the machine and provides results about the situation and what to do with it. It will be studied two cases, one of them using machine learning classical techniques to determine the forces applied to a unnamed aerial vehicle and other using deep learning techniques like neural networks in the structural health monitoring area.

Complete after the research is done.

Keywords: machine learning, structural health monitoring, unnamed aerial vehicle

LIST OF FIGURES

LIST OF ACRONYM

AI	Artificial Intelligence
ANN	Artificial Neural Networks
BD	Big Data
CNN	Convolutional Neural Networks
DL	Deep Learning
FEM	Finite Element Method
IoT	Internet of Things
MEMS	Micro Electromechanical Systems
ML	Machine Learning
MLP	Multilayer Perceptron
NN	Neural Networks
SHM	Structural Health Monitoring
UAV	Unnamed Aerial Vehicle

CONTENTS

1 INTRODUCTION

The use of Artificial Intelligence (AI) is very present nowadays [33, 43, 44]. This area of statistics neither is new nor started just now with the autonomous cars and voice assistants [41], but it is clear that in the last years it has been increasingly gaining more popularity. This happens mainly because of the advances that the World Wide Web has been had over the years [34, 13], since dial-up internet connection, back in the eighties, until now, with broadband internet and smartphones equipped with 5G connection. Another factor is that in the past, the cost to get a large capacity of storage memory was significantly more expensive than it is now, what makes today cheaper and easy to get memory to store information [23]. With the amount of data available, the evolution of internet and storage capacity, now it is not difficult to obtain, keep and analyze databases to make decisions [17].

AI application is everywhere and today, more than ever, it is easy to realize that. Either to get multimedia recommendations on streaming platforms, like occurs at Netflix, YouTube, Spotify, and so many others platforms [12], or to make predictions on the financial market and sports betting [40, 30, 26], AI is there behind the scenes making all the magic happen. Evidently there is nothing really magical about them, it is pure mathematics combined with a programming language that produces the algorithm capable of doing those things [24, 3, 45, 46]. The launch of ChatGPT–3, and shortly thereafter ChatGPT–4, has shown the power of those technologies and how they can change the way people do things [10, 9, 36, 6].

Getting into the smart systems application, the use of AI is widely used to Structural Health Monitoring (SHM), which is heavily used in the aerospace and civil fields, [5, 59]. The level and the complexity of the AI to be applied to monitor the structure, whether is going to use Deep Learning (DL) and Neural Networks (NN) or simpler methods of Machine Learning (ML) like regressions, is determined by the problem itself and the results desired [19]. In some cases, the standards methods use numerical techniques and they may not be feasible, especially when there is a huge data to be analyzed. Thus, taking the AI road is an alternative to get the needed results for the monitoring in a more practical way [52, 54].

Still in this context, but in the field of Unnamed Aerial Vehicle (UAV), the use of AI can be combined to integrate UAV through wireless communication networks [32] what can be useful in the agriculture sphere [1] with technologies like Internet of Things (IoT) [56, 55]. Also, the use of the AI can be subtle, such as the use of a built-in MATLAB function to make a simple NN to determine the final pose of a UAV based on the initial pose and the forces applied on it [21], or can be more sophisticated, like the use of ML and DL algorithms to predict materials properties, design new materials, discover new mechanisms and control real dynamic systems [25, 2].

It is clear, therefore, that AI can transit into different fields, such as entertainment, business, health care, marketing, financial, agriculture, engineering, among others [47, 60, 16, 57, 39, 42, 22]. The use of the Big Data (BD) can not only make it clear the scenario to be studied, but also to support making strategical decisions [27, 31]. The internet and hardware improvement [7], alongside the facility to storage data with accessible costs, encourages the AI use due to the benefits it can provide.

1.1 Objective

To develop an AI algorithm based on NN to apply in smart systems. The main goals are:

- to determine the forces used to move an UAV based on its initial and final pose;
- to detect railways cracks through piezoelectric signal for SHM.

2 METHODOLOGY

This chapter deals with the history, the main concepts and some practical cases of SHM inside the industry and academic area, besides showing how it may be used in the railway crack detection context. Next, in the dynamic field, it will be studied the main mechanical concepts to get the necessary understanding to an UAV motion as well the basics to know how an UAV can be controlled. Then, it will be shown the mathematics behind the algorithms of deep learning that will be implemented in the Chapter 3. Finally, the way how the algorithms are going to be implemented and the tools necessary to achieve the desired neural network.

2.1 Structural Health Monitoring

2.1.1 Definition

According to Balageas et al. [8], the SHM main purpose is to provide, during the life of a structure, a diagnosis of: the state of the constituent material; the different parts of the structure; and the full assembly of each part that makes the structure as a whole. It is an improved way to make non-destructive evaluation. It can be applied in several areas such as civil infrastructure, like bridges and buildings; aerospace, like airplanes and spaceships; and mechanical, like machines.

Furthermore, it also can be associated as an analogy to the human nervous system. Just like the sensors send a signal to the central processor, the human senses send a signal to the brain to make the recognition of what is happening, as shown in the Fig. 2.1.1.

2.1.2 Brief History

The SHM development began back in the 20th century and it has been coupled with the evolution of the digital computing hardware, what allowed the costs of the applied techniques less expensive over time.

It all starts back in the early 1970s and 1980s. The oil industry tried to develop vibration-based damage identification methods for offshore platforms by simulating damage scenarios, examining the changes in the resonant frequencies and correlating them with those measured on a platform. In the same period, the aerospace community

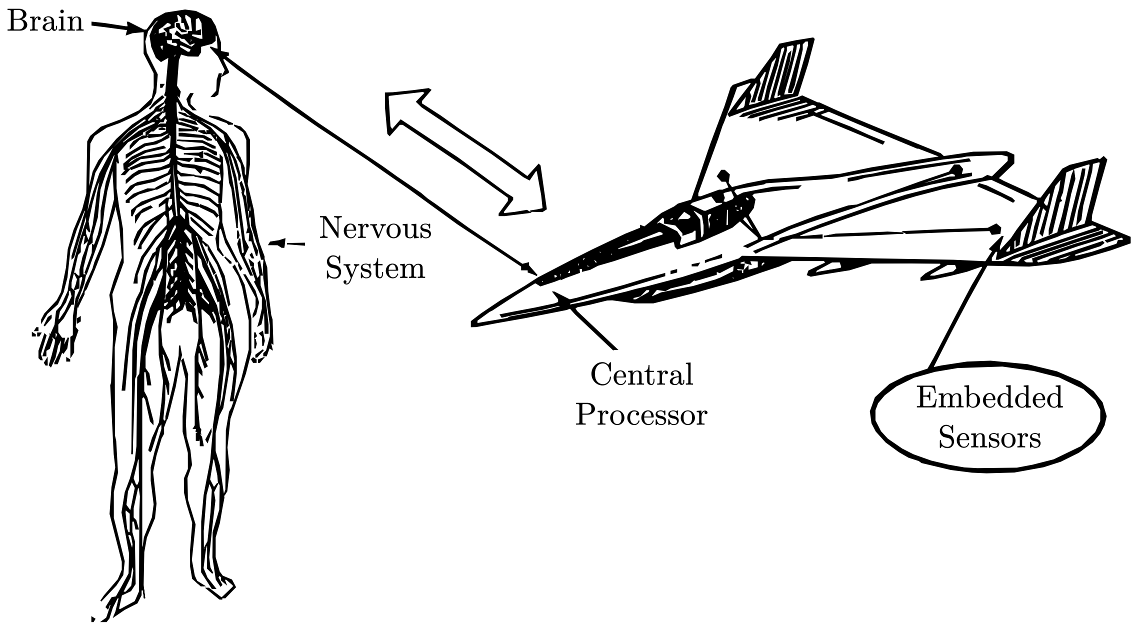

Figure 2.1.1. SHM and human nervous system analogy. Source: Balageas et al. [8]

studied vibration-based damage identification along with the development of the space shuttle. From that, it was developed the shuttle modal inspection system which aimed to identify fatigue damage in components like fuselage panels and control surfaces. The system was so successful that all orbiter vehicles had been periodically subjected to this test. Also, the civil engineering community studied vibration-based damage evaluation of bridge structures and buildings in the late 1980s [18].

From the late 1990s to the early 2000s, Sohn et al. [53] showed the evolution of the techniques used in SHM, analyzing mainly the following factors: the operational evaluation; data acquisition and cleansing; feature extraction; and statistical modeling for feature discrimination. He also verified that the statistical patter recognition had not been embraced by the researchers to be more often used in such matter.

Nowadays, in order to contour inherent issues of SHM methods, as large computational effort and hand-crafted work that results in poor classification performance, many deep learning techniques have been used, such as Convolutional Neural Networks (CNN) [4].

2.1.3 Main Techniques

Accelerometers

The use of accelerometers is consolidated in the engineering community to be used in several areas and it is present in the people daily life in things like game consoles, smartphones, and tablets.

Micro Electromechanical Systems (MEMS) sensor have several applications in measuring linear acceleration or angular motion along axis as an input to control a system. MEMS accelerometer sensors often measure the movement of a mass with a position measuring interface circuit that is converted into a digital electrical signal by an analog-to-digital converter for digital processing [15].

In SHM situation, the accelerometers are in the MEMS. The MEMS are, then, embedded in the structure and can provide information about the structure by detecting low-amplitude and low-frequency vibrations that are not always viable with the conventional low-cost sensor boards [48].

There are many others sensors used in vibration-base techniques like velocity and displacement sensors, however the accelerometers are widely used for this purpose.

Optical-Based

The use of digital cameras to detect any kind of irregularity in the surface is also a way to monitor the structure, mainly in the surface areas. The camera itself may be static in a strategical position that allow it to provide good images to be analyzed or can be embedded in the structure itself or in an UAV that will surround it.

To automate and improve the accuracy of the damage detection, image processing techniques are employed, that being a non-conventional approach [51]. In the civil engineering context, it is commonly utilized computer vision to damage detection [20] and also UAV integrated in the same local as the structures for SHM [50].

Many of the images obtained can have their not only the images improved by AI, but also the analyses can take advantage of it.

Piezoelectric Materials

When dealing with acoustic-based techniques, the use of piezoelectric materials as sensor is a great choice due to its ability to respond to stimuli, incorporation, and compatibility with construction materials. Beyond that, these materials are relatively cost-efficient and can sense vibrations in the structures they are installed [28].

Piezoelectric materials and their main property were discovered back in 1880 [14]. The phenomenon is that by the application of pressure in those kinds of materials in the correct direction, it is observed the production of a potential difference and consequently an electrical charge. Examples of materials that are piezoelectric are quartz, zinc, sodium chlorate, tourmaline, calamine, topaz, tartaric acid, cane sugar, and others [11].

The application of these materials in SHM is basically to install the piezoelectric sensor in the structure intend to be monitored and through the tension or compression in it done, a sign will be sent to the central system by the potential differential. The signal indicates that something not usual is happening in the structure. Of course there are levels of the signals and each case must be evaluated in its context. In the last years the use of piezoelectric materials has been capable to identify failures, like the presence of delamination damage, as long as the piezoelectric sensors are close to the damage [37].

2.1.4 Railway Cracks

Train is one of the most used means of transportation around the world, either to transport people or groceries, therefore, there are inherent problems in the attached to it. One of the most common problems is the crack on the railway track, mainly due to the expansion and contraction caused by the heat and to constant pressure because of the wagon.

The crack in a railway is considerable problem because it may cause fatal accidents since the wagon is able to leave the railway. In this scenario, many methods are used to detect the crack or to foresee it before any misfortune happen. Karthick and Ramalingam [29] proposed a system to identify the cracks and prevent the accidents. One of its advantages is that if some crack is detected on the track, the train starts to slow and stop before it passes by there. Other method includes the use of sensor coupled in the track that allow to detect the crack and send a signal to the command center through IoT [49].

The use of piezoelectric materials for SHM is very common, as seen in the Section 2.1.3. Loveday [35] presents a system where piezoelectric transducer are installed along the railway track. They receive an electrical wave and send it, then, a signal to the receiver, making it possible, also through Finite Element Method (FEM), to detect any inconsistency that should not be there.

There are, hence, lots of methods that can be used to detect and prevent accidents in railway tracks. Putting they together and optimize them with SHM techniques are an efficient way of improve the railway ecosystem.

2.2 UAV Dynamics

2.3 Neural Networks

2.3.1 Deep Learning

The concepts of deep learning studied in this section is going to be based on the work of Goodfellow et al. [24] and the documentation of PyTorch[1] and MATLAB[2].

There are several definitions of AI [58], but the computer scientist McCarthy [38] defines it as "the science and engineering of making intelligent machines, especially intelligent computer programs.". He also states that "it is related to the similar task of using computers to understand human intelligence, but AI does not have to confine itself to methods that are biologically observable.".

The big area of study is the AI and it includes several branches like fuzzy logics, robotics, machine learning and so on. The later one, in turn, is another field with also some branches and one of them is the deep learning. This can be represented in a Venn diagram, as the Fig. 2.3.1 shows. However, all the three terms can be interchangeable in the major context.

The deep learning history goes back to the 1940s and it had several names over the years. It was called by *cybernetics* (1940s–1960s), *connectionism* (1980s–1990s), and from 2006 until now is known as *deep learning.* The DL models were engineered systems inspired by the biological brain and they were denominated Artificial Neural Networks (ANN). One of the motivations of the neural perspective was to understand that the brain provides a proof by example that intelligent behavior is possible and try to reverse engineer the computation principals behind the brain, duplicating its functionality.

DL today goes beyond the neuroscientist perspective and it is more of general principle of learning multiple levels of composition.

[1]https://pytorch.org/docs/stable/index.html
[2]https://www.mathworks.com/help/matlab/

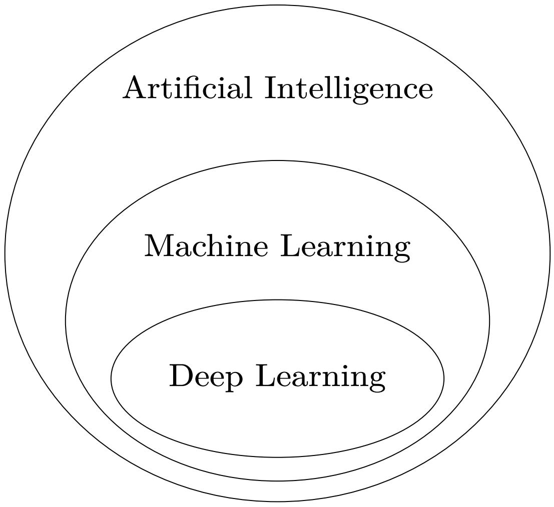

Figure 2.3.1. Subareas of Artificial Intelligence

2.3.2 Multilayer Perceptron

Perceptron

A perceptron is a supervised learning algorithm that provides binary classifiers. It is the simplest kind of ANN, but the complex ones are based on it and it serves to solve many problems yet.

The principle is quite simple, from the input data $\mathbf{x}$ and initial random weights $\mathbf{w}$, it returns the weighted sum $f(\mathbf{x}, \mathbf{w})$. This is graphically represented in the Fig. 2.3.2.

$$f(\mathbf{x}, \mathbf{w}) = \sum_{i=1}^{n} x_i w_i = x_1 w_1 + x_2 w_2 + \cdots + x_n w_n \tag{2.3.1}$$

where $\mathbf{x}$ is a vector containing the input data and $\mathbf{w}$ is a vector containing the weights, both with n elements.

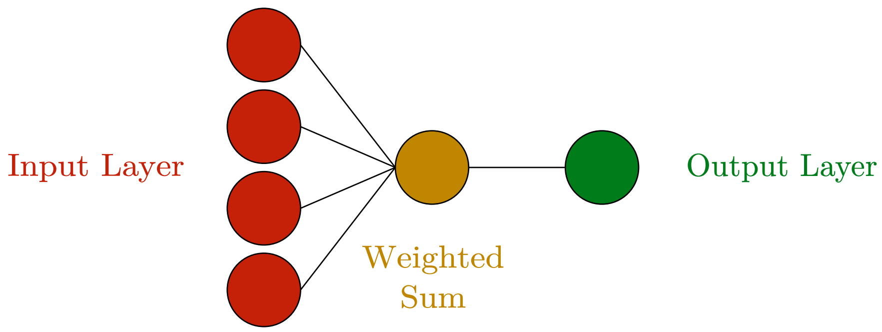

Figure 2.3.2. Perceptron Scheme. It is a simple machine learning algorithm that provides a binary output. It resembles a human neuron: input layer data is equivalent to the dendrites; hidden layers are the equivalent of the axons; and the output layer are the equivalent of the nerve ending.

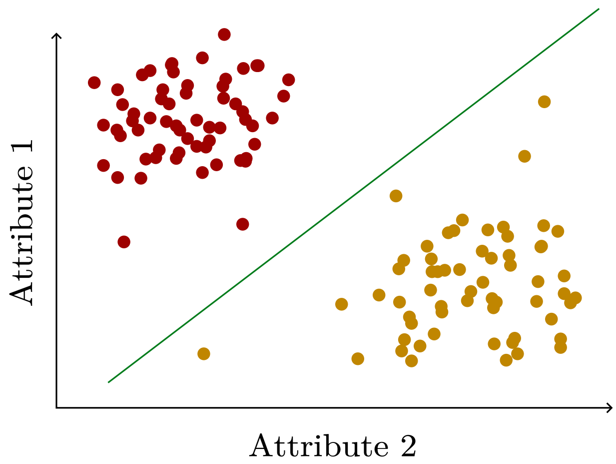

Figure 2.3.3. Perceptron Behavior. It is a binary classifier.

It splits the data with a straight line classifying them in two groups and that is the reason it is a binary classifier.

Surely, for the first iteration, the output should not be the best one and the procedure must begin from the start, but now with the new values obtained. Then, for each iteration it tends to get a better and learn to label each data received.

A Multilayer Perceptron (MLP), also known as *deep network*, is the essence of DL. Basically, it is a mathematical function, formed by composing many simpler functions, mapping some set of input values to output values.

2.4 Algorithm Implementation

The code implementation will be pragmatical and the lines of the code will not be fully explained. The frameworks methods will not be explained either, but their documentation are reasonably comprehensive with previous programming knowledge,

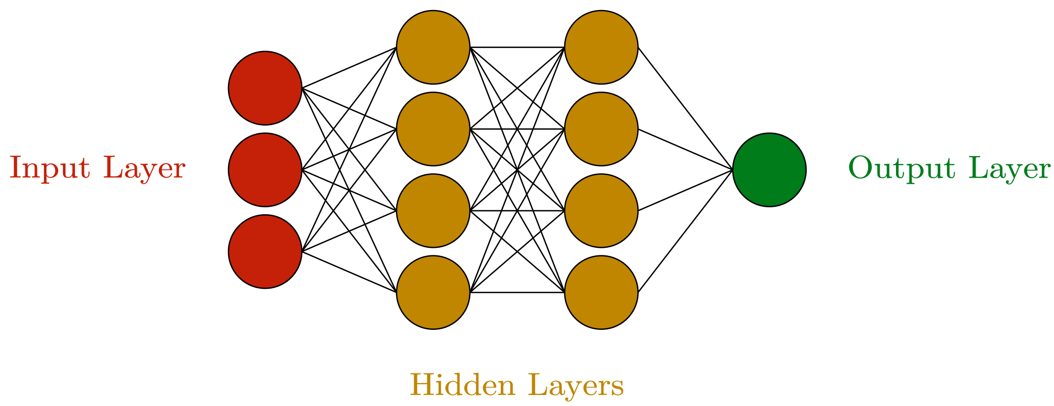

Figure 2.3.4. Multilayer Perceptron Scheme. The figure show two hidden layers, totalizing eight neurons. A MLP accepts multiple hidden layers and neurons. It can also have several outputs.

especially in Python and MATLAB, and they are going to be linked whenever possible.

While the engineering goal of AI is to solve real-world problems using it as an equipment, the scientific goal is to determine which ideas explain the various sorts of intelligence [58] and here the current objective is to use AI from the engineering perspective.

2.4.1 MATLAB Algorithm to Determine the Forces

2.4.2 PyTorch Algorithm to Detect Railway Cracks

3 RESULTS AND DISCUSSION

4 CONCLUSION

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