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Exploratory research on analysis of seismic signals towards crustal deformation estimation

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Proposta de Tese para obtenção do Grau de Doutor em

Engenharia Informática

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Abstract

This document presents the project thesis named as "Exploratory research on earth signals towards the prediction of crustal deformation estimation." This research will extend previous research into the realm of earth signals. The main objective of this work will be test and adapt well-known AI algorithms to earth signals as to assets its validity as predictors of earth crustal deformation, helping, we hope, the prediction of earthquakes. It has known that crustal deformation may disturb the lower ionosphere thought various coupling mechanisms capable of causing earthquakes (seismogenic) and the points on a map that indicate the places simultaneously affected by an earthquake shock (coseismic) periods. The Very Low Frequency (VLF) signal radiated from ground-based transmitters is affected when it passes close the disturbed area. VLF ground receivers could record these disturbances. These disturbances could be studied using full wave simulation and models. However, this proposal has other objectives that need to be accomplished so that the research work is successfully done, namely a development of a model that can predict in a temporal space large enough to enhance measures to protect human live and goods. After the literature study on methods created and used by other authors, the process of developing the new predictive model and creation of new algorithms starts with designing the predictive model framework. During the literature study, many problems had been identified, such as feature selection; different VLF, Low Frequency (LF) propagation on soil composition, afterwards a study about the best methods used for dimensionality reduction is necessary to identify the best method to obtain the best data input for the prediction model. The research for this thesis will be done in the Assisted Living Computing and Telecommunications Laboratory (ALLab), a research laboratory created in the context of both the Instituto de Telecomunicações (IT) and the Universidade da Beira Interior (UBI).

Keywords

Seismic data processing, Seismic ambient noise, Time-lapsed monitoring, Deterministic and Stochastic Optimization, Machine Learning.

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Acronyms

ALLab	Assisted Living Computing and Telecommunications Laboratory
AGW	Atmospheric Gravity Waves
P-Wave	Primary Wave or Pressure wave
S-Wave	Secondary Wave or Shear Wave
VLF	Very Low Frequency
LF	Low Frequency
IT	Instituto de Telecomunicações
UBI	Universidade da Beira Interior
CDE	Crustal Deformations Estimation
CDEM	Crustal Deformations Estimation Methods
TEC	Total Electron Content
ULF	Ultra Low Frequency

Chapter 1

Introduction

1.1 Introduction

The introductory chapter starts by presenting the motivation and scope of this proposal, then, the problem statement is defined, the objectives and expected results are presented, and finally, the organization of the document is presented.
Technological advances in AI have revolutionized the way information is treated and processed. These advances have allowed the development of new tools that help professionals in the effort of prediction major crustal deformation, namely on well kwon seismic places. The study of full wave signal models captured by VLF/LF, AGW receivers as well the identification of some determining features that can be used in AI brought some hope in the prediction of earthquakes. So far, the context of the collected data provides 'in situ' knowledge solutions, yet not satisfying. We hope, with this work, the development of better predictive algorithms regardless of the place where data is collected. The main objective of this PhD research is the development of algorithm(s) for the prediction of crustal deformation estimation, eg, prediction of earthquakes. The first research issue is to scan seismic archive, then define new methods for compute cross-correlation and hopefully develop a method, in the AI field with data from full wave study that can help on the forecast of earthquakes. This chapter presents the research scope of the thesis in section 1.1. Next, in section 1.2, the problem statement and objectives are presented. In section 1.3, the research hypothesis is presented. Finally, in section 1.4, the organization of this document is presented.

1.2 Motivation and Scope

Crustal deformation may disturb the lower ionosphere though various coupling mechanisms during their seismogenic and coseismic periods. The VLF signal radiated from ground–based transmitters is affected when it passes near the disturbed region above the seismogenic area, and this variation can be recorded from ground based VLF receivers [2].
Several methods have gained significance in recent years. This proposal presents the research work plan involving data analysis and prediction algorithms using these methods, namely neural networks, heat maps and genetic algorithms.
The scope of this research proposal covers the following areas and goals:

- VLF, LF and Atmospheric Gravity Waves (AGW) propagation study;
- Multi-data acquisition and analysis;

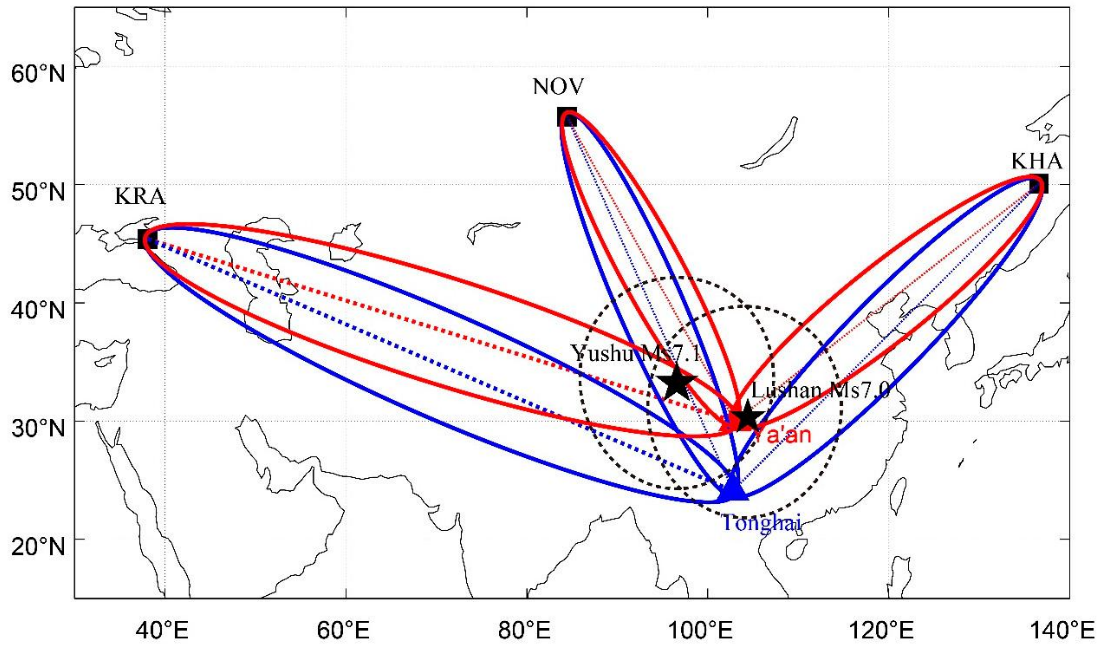

Figure 1.1: A sketch of the observation region. The three VLF transmitters in Russia denoted by black square, three receivers in China denoted by triangles (red for Ya'an, blue for Tonghai), the black pentagram represents the epicenter of the Yushu earthquake and the Lushan earthquake, the black dashed circle represents the preparation zone of the Yushu earthquake. The red and blue ellipse denotes the 5th fifth Fresnel region of frequency F1 (11.9 kHz).

- Context correlations;
- Learning algorithms.

The prediction results give more or less accuracy in a time window, depending on the amount of instruments used, the time of the day they are collected and data collection. Several techniques are used for prediction as described in chapter 2 such as full wave method to seek a solution for Maxwell equations, a based geophysical inversion using Bregman and proximity operators and noise-based ballistic wave passive seismic body waves monitoring. Some works, refer neural networks, heat maps and genetic algorithms as promising methods for predicting earthquakes.
The proposed work will hopefully improve the quality of prediction by offering novel knowledge. With this research work, different regions, different day time recorded data and different world regions are used to be inputs of utmost importance for improving the accuracy and reliability of the predictive algorithms.
We acknowledge that accurate and properly localized P- and S-wave velocity temporal anomalies at depth is intrinsically limited by the complexity of scattered, diffracted waves. In order to mitigate this limitation, we propose a complementary, novel, passive seismic monitoring approach based on detecting weak temporal changes of velocities of ballistic waves recovered from seismic noise correlations. This new technique requires dense arrays of seismic sensors in order to circumvent the bias linked to the intrinsic high sensitivity of ballistic waves recovered from noise correlations to changes in the noise source properties.

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The perspective of applying this new technique to detect continuous localized variations of seismic velocity perturbations at a few kilometres depth paves the way for improved in situ earthquake, volcano and producing magma reservoir monitoring.

1.3 Problem statement, Objectives and Expected Results

Nature is generically unpredictable, because of the exponential features/conditions that must be taken in account, and earthquakes do not escape to this reality. When a major earthquake occurs, the destruction of human infrastructures and the loss of human lives are overwhelming. We hope that the data collected and posteriorly threated by VLF/LF radio wave stations and AGW stations, who give us how a numeric picture of the interior movements of the earth in terms of internal forces, could be a powerful input for some AI technics for predicting such natural disasters. Our objective is, using that data, develop some method involving neural networks, heat maps or genetic algorithms for the prediction, within a human feasible timeline, of such episodes.

1.3.1 Research questions:

Question 1: How much extra information we can extract from ambient noise data comparing to the earthquake waveforms to be utilized in crustal deformation estimation;

Question 2: How much signal processing algorithms are efficient to extract key information from ambient noise data towards estimation of crustal velocity deformation;

Question 3: How much the obtained crustal velocity deformation attains pragmatic information towards predicting natural hazards;

The objectives and expected results for this PhD project can be summarized as:

1. State-of-the-art study:

   (a) Crustal Deformations Estimation (CDE). Revision of underlying principles: Search Space, Search Methods, Search Strategy (Random, Evolutionary, Reinforcement Learning, Gradient-based, Bayesian Optimization) and Performance Estimation (partial and full train, lower fidelity estimation, earning-curve extrapolation, weight inheritance, sharing, one-shot models). Comparative analysis of existing methods and categorization based on the aforementioned principles. Study of relevant tools, benchmarks and frameworks.

   (b) Neuroevolution. Perform a bridge from traditional evolutionary methods, that evolve simpler architectures, to more recent, deep learning ones. Comparative analysis and study the possibility of integrating/improving such systems.

   (c) Crustal Deformations Estimation Methods (CDEM). Study and analysis of different CDEM methods, and components.

2. Development and validation of a novel CDE method that leverages information of human-designed networks, without limiting or enforcing the search space or exploration.

3. Improvement of the CDE methods by allowing unforeseen and uncommon operations to be sampled. Furthermore, develop novel modules that allow the creation of new operations. This is important to improve CDE generalization.

4. Publication of the work, on specialized conferences/journals. The work will consist on reproducible research, making the implemented methods and framework public.

5. Writing of a solid PhD thesis, sustained by several contributions to the field of CDE.

1.4 Document Organization

The document is structured into three chapters. In chapter 1, an introduction presents the research topic and the scope of the thesis proposal. In this chapter different problem around this research topic are addressed, objectives and research questions for this PhD thesis proposal are presented. In chapter 2, overviews on the state of the art are given. The State of the Art starts with a survey analysis of exploratory research on earth signals towards prediction of crustal velocity changes and related research works published about prediction of crustal velocity changes. We also give discussion on information about proposed methods, datasets used, best practices to compare our propose method. Chapter3 presents the work plan for the thesis proposal and starts with the research method where each phase is presented, and the project schedule. The chapter continues with expected contributions, results and dissemination. Finally in chapter3, section 3.4, the conclusions of this document.

Chapter 2

State of Art

In this part of the research work, a preliminary study of the research work conducted on this topic, including the methodology and in-detailed implementation information of several proposed methods is presented.

2.1 Introduction

Catastrophic events like destructive earthquakes and massive volcanic eruptions are caused by different types of crustal deformation unraveling themselves as short-time scale stress and pore pressure accumulation regime around potential faults and magma reservoirs [3, 4, 5]. This fact motivates scientists to devise state-of-art investigation methods to monitor crustal deformation to foresee catastrophic tectonic and volcanic events. Among different study methods in earth sciences, the seismological methods are more efficient and attractive due to their high penetration depth. Specifically, there is a direct connection between P- and S-wave seismic velocity variations to stress and pore-pressure perturbations.

For many years there have been debates among the scientific community about the possibility of monitoring crustal deformation by analyzing time-lapsed passive seismic data. However, due to an embedded high level of uncertainty in hypocentral and initial time estimation of local earthquakes, estimating tiny percent ($\sim$1 percent) crustal velocity change [6] by using passive seismic tomography has always remained a dream to scientists in the geophysical community. Although an evident preseismic anomaly was observed by an active seismic monitoring [7], massive operative costs and minimal area coverage of active seismic studies make the application of the method impossible for worldwide investigations.

Over the last decade, noise-based monitoring studies have been widely introduced as a workaround to limitations of passive seismic method, by introducing continuous time-lapsed green functions which can be used to estimate crustal velocity changes [8, 9, 10].

Over the past decades, the introduction and development of the ambient noise cross-correlation concepts have opened new doors to exploring underground structures. Furthermore, ambient noise-based time-lapsed subsurface monitoring methods have emerged due to the feasibility of reconstructing the continuous empirical Green's functions [11]. It is used as a tool for crustal deformation investigation by tracking crustal velocity changes that, in this case, do not depend on the occurrence of earthquakes. Here, we shortly review the process:

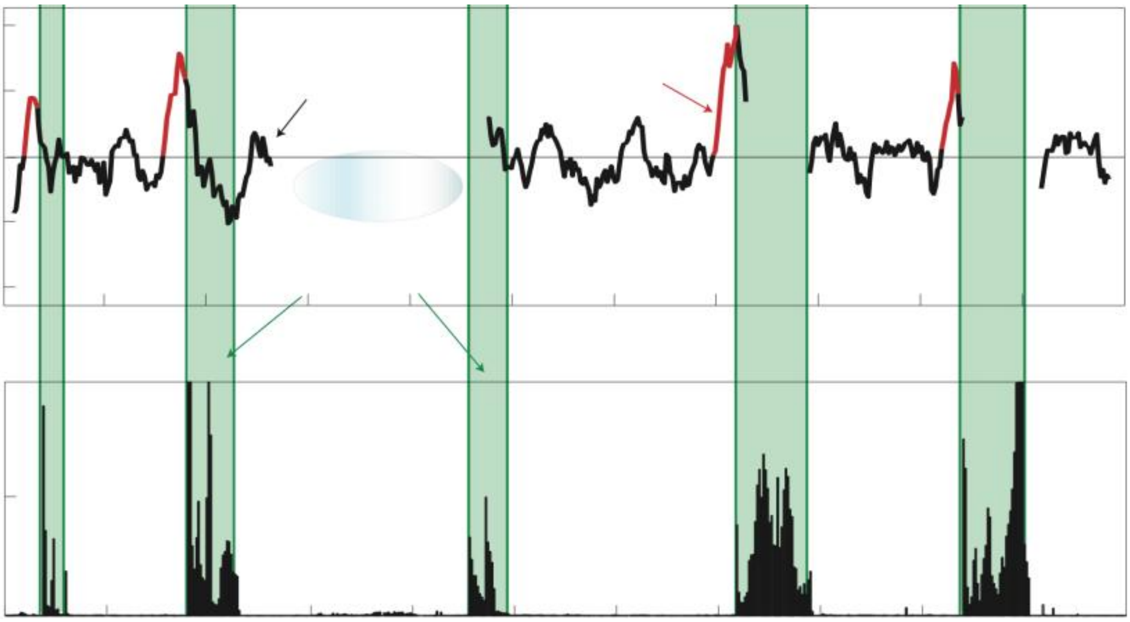

Figure 2.1: Crustal velocity variation before volcano eruptions of the Piton de la Fournaise volcano vs seismic energy. (Figure from [1]).

2.2 Ambient Seismic Noise-Based Monitoring

An original introduced version of ambient noise-based seismic wave velocity monitoring is a coda wave interferometry, which was based on the concept of coda wave-based seismic velocity monitoring [12]. In this methods the phase shift of seismic waveforms between earthquake doublets is retrieved along seismograms. In a more advanced version, [13] proposed a similar concept to estimate the time variations by incorporating different lapse time to evaluate the relative seismic wave velocity.

This evaluation assumes that changes in the wavefield are homogeneous; therefore, they obey a linear relationship in which a travel-time shift is opposite seismic velocity changes:

In this way, several techniques for noise-based monitoring have been developed, including moving-window cross-spectral analysis, the stretching method, dynamic time wrapping, wavelet cross-spectrum analysis, and a combination of these measurement methods, with either a Bayesian least-squares inversion or the Bayesian Markov chain Monte Carlo method. We briefly state the principles underlying the different methods and their pros and cons. By elaborating on some typical noise-based monitoring applications, we show how this technique can be widely applied in different scenarios and adapted to multiples scales. We list classical applications, such as following earthquake-related co- and postseismic velocity changes, forecasting volcanic eruptions, and tracking external environmental forcing-generated transient changes. By monitoring cases having different targets at different scales, we point out the applicability of this technology for disaster prediction and early warning of small-scale reservoirs, landslides, and so forth. Finally, we conclude with some possible developments of noise-based monitoring at present and summarize some prospective research directions. To improve the temporal and spatial resolution of passive-source noise monitoring, we propose integrating different methods and seismic sources. Further interdisciplinary collaboration is indispensable for comprehensively interpreting the observed changes.

- Ground-based observation points and satellite readings of electromagnetic energies in a wide range of frequencies;
- The discovery of very high Ultra Low Frequency (ULF) signals in Loma Prieta (California) earthquake;
- The acknowledgment that rocks under pressure could generate electrostatic and electromagnetic radiation in frequencies from 10 Hz to 10 MHz;

Chapter 3

Research Work plan

3.1 Introduction

The work plan [14, 15] consists in the definition of the research method for the PhD Thesis proposal titles as "Exploratory research on earth signals towards prediction of crustal deformation estimation". This plan starts with presenting the research method, the expected contributions and results and finally, the expected dissemination.

This PhD thesis proposal will address the problem of developing prediction algorithms for exploratory research on earth signals towards prediction of crustal deformations estimation. The solution is composed by techniques for the feature selection in order to resolve problems of dimensionality, and supervised and unsupervised learning algorithms. This study will be lead at the ALLab, part of IT at University of Beira Interior, in Covilhã. This study will be done under the supervision of Prof. Doutor Nuno Manuel Garcia dos Santos and Doutor Hammzeh Mohammadi-Gheymasi In the next section, the research method is presented.

3.2 Research Method

The research method for the thesis is divided in five main phases:

1. Research preparation - This first phase is a preparatory phase where it is done a background research about the thesis proposal.
2. State of the Art - The first task of this phase, literature study, is currently in development. Part of this study is presented in chapter 2 – State of the Art; For now the literature study gives some relevant information for starting the next phases mainly for the prediction model framework.
3. Data Collection - After collection, the data will be anonymised in order to prevent associations between the data and regions
4. Model Implementation - With the information presented in chapter 2 – State of the Art, the prediction model framework is designed:
   (a) Input Data and feature extraction;
   (b) Feature selection;
   (c) Distribution data for learning process;

(d) Input Algorithms for learning process;

(e) Performance Measures. After framework design, the objective is to choose the best techniques for handling data and feature selection in order to obtain the best input variables combination for the prediction algorithms. For the learning process, it is necessary to choose the algorithms for training the data and for this it is required to divide the selected data in training data and testing data. After algorithm, testing the prediction is obtained, and after obtaining the prediction results, improvements and performance analysis are done.

5. Research Findings -In this final phase, the goal is the analysis of predictive results and concluding the research. The final task of this work plan is to write the thesis.

3.3 Research Schedule

The research schedule for this PhD proposal is divided into 36 months, and can be seen in detail in Figure 3.2, where the tasks, time allocation and milestones are presented. In the next paragraphs we explain in detail each one of the tasks/objectives. References to a given task, use Figure 3.2 as a basis.

We expect to have several novel contributions to the field of crustal deformation estimation, a public framework that will allow both experts and non-experts to develop crustal deformation estimation methods, and a solid PhD thesis, justified and supported by strong contributions.

3.3.1 Conferences and Journals

We intend to continuously publish the work that is being developed in excellent conferences and journals, which ensures that the work is reviewed extremely carefully, and thus, that it is worthy of being published. In table 3.1, we list the conferences and journals that we found to be related with the topic of the proposed method. In this table, we show the conference/journal name, the frequency, and the CORE ranking for conferences and quartile for journals, as it is the official rankings used by European institutions.

Denote that the conferences and journals presented do not restrict the scope of publications of this work, as they just present a guidance of where to publish our work. As other works start to be published in other venues, we will take that into consideration, as they might be more appropriate or focused in our research topic.

3.4 Conclusions

In this section we outlined the approach we will take towards the PhD research, which will be based on the Construction technique based on problem solving. Then, we outlined

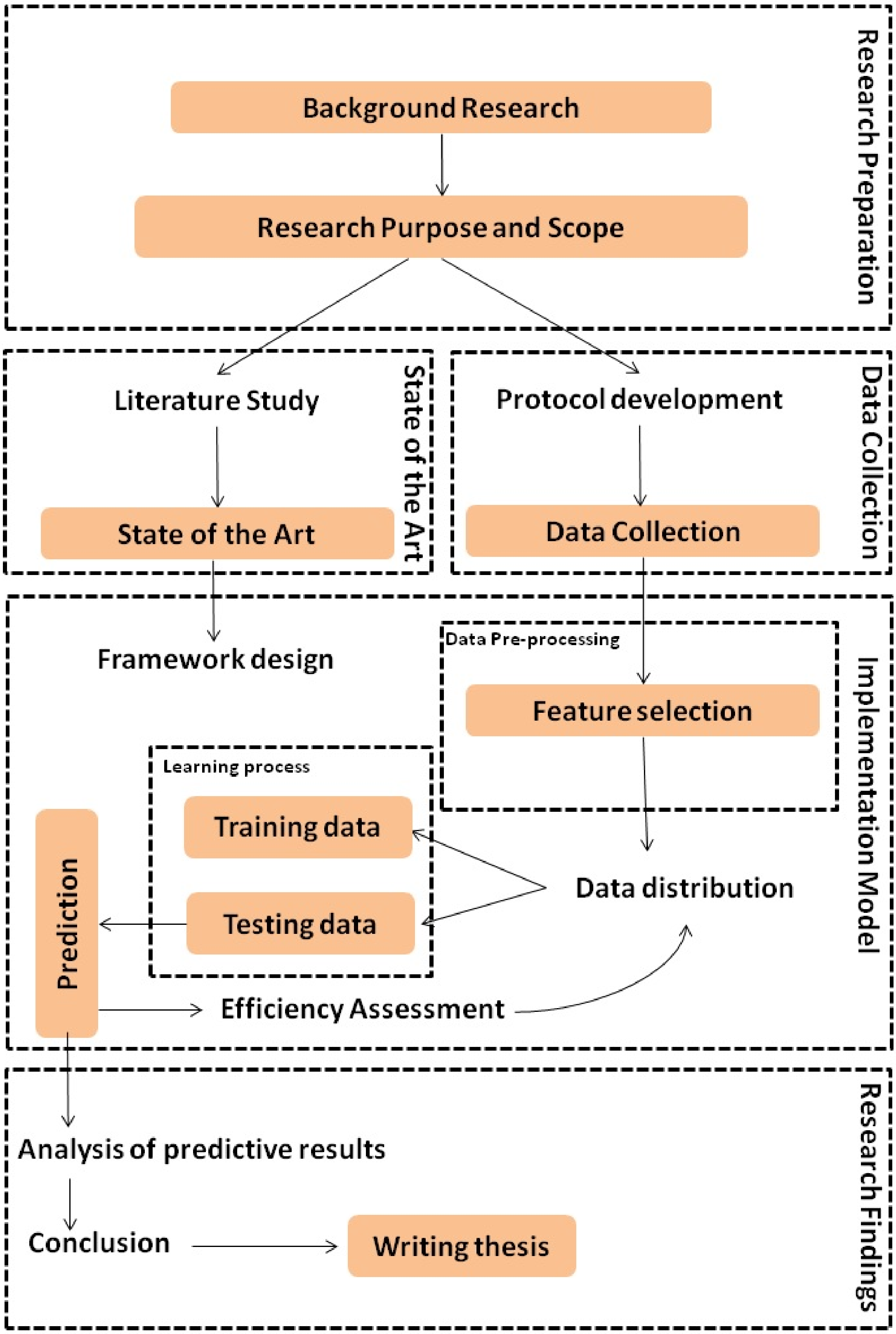

Figure 3.1: shows a scheme with the five main phases of the work plan, described in detail.

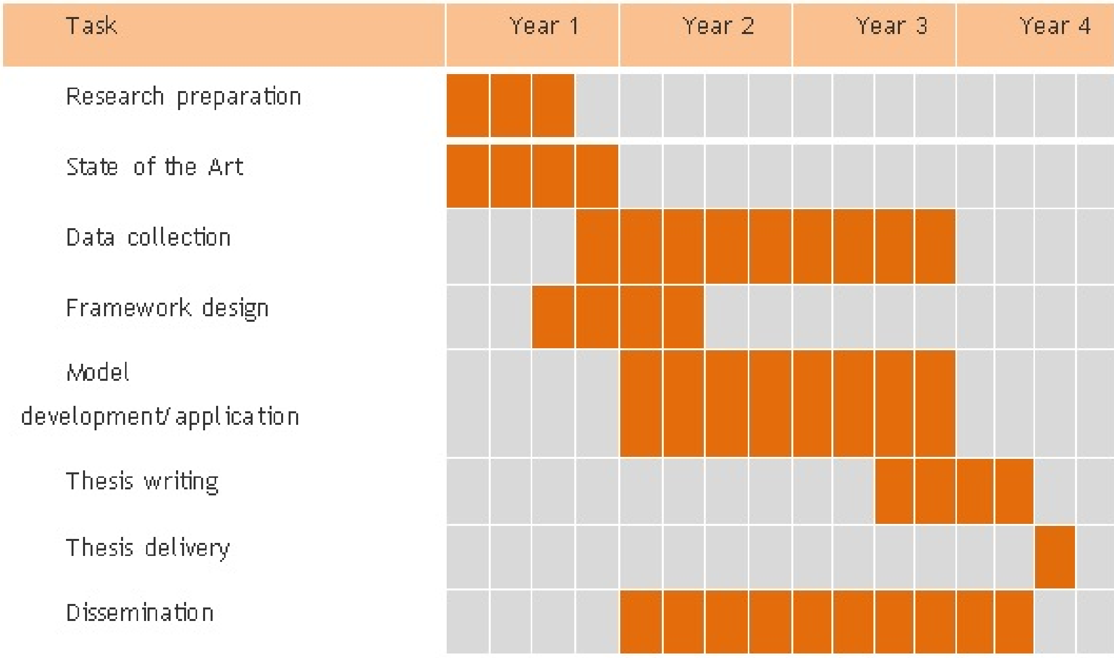

Figure 3.2: Work schedule.

Table 3.1: Conferences and journals that are related to our research topic.

Conference	**CORE**	**Frequency**
IEEE Conference on Computer Vision and Pattern Recognition	A*	Yearly
Advances in Neural Information Processing Systems	A*	Yearly
International Conference on Machine Learning	A*	Yearly
National Conference of the American Association for Artificial Intelligence	A*	Yearly
International Joint Conference on Artificial Intelligence	A*	Yearly
International Joint Conference on Artificial Intelligence	A	Yearly
International Conference on Learning Representations	-	Yearly
International Conference on Pattern Recognition	B	Yearly
IEEE International Conference on Tools with Artificial Intelligence	B	Yearly
Journal	**Quartile**	**Frequency**
IEEE Transactions on Pattern Analysis and Machine Intelligence	Q1	12 issues per year
IEEE Transactions on Neural Networks and Learning Systems	Q1	12 issues per year
Journal of Machine Learning Research	Q1	8 issues per year

the research schedule for the next 36 months, as well as what tasks and milestones we intend to complete and achieve. At the end, we presented the conferences and journals that currently fit the scope of this project, and that we will aim to publish at.

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