REVIEW

on a dissertation for awarding the educational and scientific degree "Doctor"
scientific specialty „Communication Networks and Systems"
professional field 5.3 Communication and Computer Engineering

Author of the dissertation: **MSc. Eng. Petar Rosenov Tomov**
Title of the dissertation: **Time series forecasting with artificial neural networks**

Reviewer: **Prof. Milena Lazarova-Mitseva, PhD**
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The review is prepared in my capacity as a member of the Scientific Jury and a reviewer in the procedure for awarding the educational and scientific degree "Doctor" as confirmed by Order №114/04.05.2022 of the Director of IICT–BAS and based on the decision of the Scientific Council of IICT-BAS (Protocol №4/27.05.2022) and the decision of the first meeting of the Scientific Jury from 10.05.2022.

The review is based on the following documents:

- Dissertation for awarding the educational and scientific degree "Doctor";
- Abstract of the dissertation (in Bulgarian and in English);
- Declaration of originality of the obtained results;
- Order №254/27.12.2018 of the Director of IICT–BAS for completion of the doctoral studies;
- Information for the fulfilment of the minimum requirements of IICT–BAS for awarding the educational and scientific degree "Doctor";
- Full text of eleven scientific publications on the dissertation topic;
- List of citations of the scientific publications on the dissertation topic.

1. Structure and content of the dissertation

The dissertation submitted for review for awarding the educational and scientific degree "Doctor" consists of 168 pages structured in an introduction, four chapters, a conclusion with a summary of the dissertation results and contributions as well as future research directions, a list of author's publications on the dissertation, a list of citations of publications and a list of bibliographic references. The dissertation also includes a list of used abbreviations, a list of figures, a list of tables, a list of listings and an appendix with program code. The list of bibliographic references contains 134 publications, all of them in English.

The dissertation is discussed and admitted for a procedure for awarding the educational and scientific degree "Doctor" at an extended meeting of the section "Information processes and decision-making systems" of IICT-BAS held on 12.04.2022.

2. Relevance of the dissertation topic in scientific and applied aspects

The dissertation is focused on an important research field related to the time series forecasting using artificial neural networks. The problem of time series forecasting is especially relevant in the recent years with the increase of the volume of the generated data in a wide variety of application areas.

Forecasting time series requires analysing a large amount of registered data using intelligent methods as well as selection and training of appropriate prediction models. Significant and intensive research efforts are aimed at proposing effective approaches and methods for forecasting time series using various approaches that not only provide accurate and reliable predictions but also guarantee the required performance and speed of the prediction according to the application area. On the other hand neural network models are widely recognised as an appropriate approach for solving a variety of problems including time series forecasting. The main disadvantage of the utilization of neural networks is the very long time required for neural network training. Therefore, significant research efforts are aimed at providing appropriate training methods that provide efficiency and performance as required by the application problem to be solved. The aim of the dissertation is to propose hybrid algorithms for accelerating learning in artificial neural networks of the multilayer perceptron type for the purpose of time series forecasting. The intensive research both in the field of time series forecasting as well as in the field of the neural network usage and neural network learning points out that the dissertation topic is relevant and closely related to crucial research problems and thus the obtained results and the dissertation contributions might be considered as important and significant.

3. Degree of knowledge on the dissertation topic and constructive interpretation of the bibliography

The presented bibliography review on the current state of the methods for time series forecasting and neural network training indicates that the author of the dissertation is deeply aware on the dissertation topic and the research problems in the field of study. The literature review is based on a large number of references, all of them in English. The constructive interpretation of the bibliography sources is the basis for the substantial formulation of the dissertation aim and the research objectives of the dissertation. The list of the references used in the state-of-the art review on the dissertation topic comprises research studies and scientific papers published in scientific journals and conference proceedings, more than half of them in the last 10 years and about 20% of then being published in the last 5 years.

4. Consistency of the used research methodology and the dissertation aim and objectives with the achieved contributions

The research methodology used in the dissertation, the dissertation aim as well as the tasks defined for the achievement of the t dissertation aim fully correspond to the dissertation topic, the achieved results and the obtained contributions. The research methodology in the dissertation is based on systematic comparative analysis of various aspects of the dissertation topic. Based on that specific approaches and hybrid algorithms are proposed to accelerate the neural network learning for time series forecasting that are experimentally evaluated and verificatio of their application is made. The suggested algorithms are based on well-reasoned decisions, proven theoretical justifications, experimental evaluation and validation of the possibilities for their practical implementation. In methodological point of view, the dissertation is logically consistent and adequate in respect to the used research methodology that ensures the achievement of the dissertation aim and fulfilment of the defined objectives of the dissertation.

5. Brief analytical characteristic of the dissertation and assessment of the reliability of the material on which the contributions of the dissertation are built

The dissertation research area is the problem of time series forecasting. The specific research field of study in the dissertation is the utilization of neural networks for time series forecasting providing relevant performance and efficiency of the neural network learning. The aim of the dissertation is to propose hybrid algorithms for accelerating learning in artificial neural networks of the multilayer perceptron type for the purpose of time series forecasting. In connection with the formulated dissertation aim and based on in-depth thorough analysis of the current research state of the problem area, several objectives related to the dissertation aim are defined: „(1) To make an overview analysis and classification of algorithms for training of artificial neural networks of multilayer perceptron type; (2) To analyse the possibility of combining different algorithms for implementation of hybrid training of neural networks of the multilayer perceptron type; (3) To propose algorithms for training of neural networks of multilayer perceptron type in distributed environment; (4) To propose an improvement in order to reduce the training time of neural network of the multilayer perceptron type; (5) To propose a software architecture for the implementation of mobile distributed forecasting calculations; (6) To develop program implementation of the proposed hybrid algorithms for training of artificial neural networks of multilayer perceptron type in order to prove their operability; (7) To make a comparative analysis of the effectiveness of the algorithms for training neural networks of the multilayer perceptron type". The definition of the dissertation aim and the specific objectives related to its achievement are justified by the author correctly and comprehensively.

The first chapter of the dissertation provides an overview analysis and classification of widely used algorithms for neural networks training outlining the advantages and disadvantages of the exact numerical algorithms and the heuristic algorithms used in the learning procedure. The possibilities for neural networks training using sequential calculations, parallel calculations and calculations in a distributed environment are also given. The second chapter presents the theoretical background of the algorithms for training neural networks of multilayer perceptron type. Modifications of some of the algorithms that are applicable in time series forecasting are proposed: determination of weights using genetic algorithm with modified selection operation; incremental approximation of time series with an approach for calculating of sine function coefficients using optimization with differential evolution and particle swarm optimisation; neural network training of three-layer perceptron type for obtaining optimal weights using an alternative activation function that provides adequate training speed and accuracy. The third chapter presents a software architecture that allows implementation of selected algorithms and proposed modifications for neural network training for time series forecasting using an object-oriented model, a relational model, communication protocols and a graphical user interface designed by the author. In the fourth chapter a comparative analysis of the utilization of some accurate numerical and heuristic algorithms for neural network training for time series forecasting is made. The experimental evaluation is based on two data sets – basic time series following a sine function and time series for the price of digital currency bitcoin in US dollars.

The suggested approaches, methods and algorithms in the dissertation are based on motivated theoretical, analytical and experimental studies. This gives me a reason to consider the results obtained in solving the defined dissertation objectives and the related contributions as reliable and practically useful.

6. Scientific and applied contributions of the dissertation

I agree and evaluate positively the contributions formulated by the author in the dissertation and in the abstract. The dissertation contributions can be classified into the following categories:

- scientific contributions:

• An approach for neural network training using genetic algorithm is suggested that utilizes a new selection operator based on population generation with a recursive descent procedure thus providing relevant speed of the used heuristic algorithms for neural network training;

• An approach for calculation of sine function coefficients in incremental approximation of time series with optimization based on the differential evolution and particle swarm optimization is proposed thus providing better approximation results;

- scientific-applied contributions:

• A new activation function for neural network elements is proposed as alternative to the usage of first derivative of a periodic attenuation activation function thus providing better speed and accuracy in time series forecasting using neural networks;

• A genetic algorithm for training neural networks of the multilayer perceptron type in a distributed environment is proposed that is suitable for neural network training utilizing parallel processing;

- applied contributions:

• A software architecture is proposed that allows implementation of mobile distributed computations based on the proposed hybrid algorithms for neural network training for time series forecasting;

• A software implementation for hybrid usage of gradient numerical and heuristic algorithms for neural network weights optimization for time series forecasting is developed as a mobile Android application.

7. Assessment of the extent of authors personal participation in the dissertation contributions

The presented content and the structure of the dissertation reveals the author's excellent comprehension on the dissertation topic and the disserttion field of study. Two out of the eleven scientific papers published in connection with the research described in the dissertation are single-authored research articles, the others are co-authored with the dissertation author being a leading author in six of them. I have known MSc. Eng. Petar Tomov since 2009 in my capacity as a professor at the Faculty of Computer Systems and Technologies at the Technical University of Sofia and I have excellent impressions from his bachelor and master degree study including as a supervisor of his final theses for obtaining the bachelor's and master's degrees.

The dissertation content, the research papers published in connection with the research described in the dissertation and all the materials presented for the procedure for awarding the educational and scientific degree "Doctor" clearly demonstrate the high quality of the scientific work of the author characterized by analytics, thoroughness and precision. Thus his personal contribution to the achievement of the presented scientific results and the dissertation research contributions is undoubted.

8. Evaluation of the author's publications on the dissertation topic

The scientific results and the research contributions in the dissertation are published in eleven scientific papers. Seven of the publications are reported at international scientific conferences held in Bulgaria and are published in the relevant conference proceedings. Four of the papers are published in scientific journals issued in Bulgaria. All publications are written in English. Two of the papers are referenced and indexed in Scopus database, the other nine are referenced in Google Scholar. Two of the publications are single-authored, the other nine are co-authored and in six of them the dissertation author is a leading paper author. Four of the publications have a total of 14 citations. The publications are made in the period from 2016 to 2021 and all of them cover the dissertation topic and comprise the dissertation results and the dissertation contributions achieved. In addition, the author obtained an award in a competition for global scalable optimization held in Borovets in the period 2-6 September 2019 as part of the International Scientific Conference "High Performance Computing'2019".

9. Significance of the dissertation's results and contributions in science and practice

The contributions obtained as a result of the research presented in the dissertation are relevant and significant and their scientific originality can be related to enrichment of the existing scientific knowledge and scientific contributions to the practice as well as creation of new and modification of existing approaches and research methods in the field of study of the dissertation and development of new approaches, methods, models and algorithms for their application. No materials are presented as part of the documents submitted for the procedure for awarding the educational and scientific degree "Doctor" that demonstrate direct practical usage of the results obtained from research studies presented in the dissertation. Nevertheless, the achieved results are important not only due to the obtained scientific and applied contributions, but also due to the possibility of their use for future research. The practical value of the dissertation research results and contributions is the possibility for future utilization of the proposed software architecture and the developed software implementation of a mobile Android application.

10. Assessment of the compliance of dissertation's abstract with the requirements for its preparation as well as its accurate presentation of the dissertation's content and contributions

The dissertation's abstract comprises 25 pages and accurately and correctly presents the dissertation objectives, the content of the chapters and the research contributions of the dissertation. It is prepared according to the requirements and adequately presents the dissertation.

11. Assessment of the fulfilment of the minimal national requirements and the additional requirements under Article 1a, paragraph 2 of the Development of the Academic Staff in the Republic of Bulgaria Act

According to the Regulations on the Implementation of Development of the Academic Staff in the Republic of Bulgaria Act for awarding the educational and scientific degree "Doctor" in the professional field 5.3. "Communication and Computer Engineering" a minimum of 50 points are required for indicator A and a minimum of 30 points are required for indicator G. The same are the requirements stated in the Regulations on the specific conditions for obtaining scientific degrees and academic positions at IICT–BAS.

The presented information for the fulfilment of the minimum requirements of IICT–BAS for awarding the educational and scientific degree "Doctor" and the materials submitted by the dissertation's author for participation in the procedure for awarding the educational and scientific degree "Doctor" show that the requirements for indicator A are fulfilled and for indicator G the total sum of the points for indicators G7-G9 is 109, which is more than three times over the minimum required points.

12. Comments, recommendations and remarks

The dissertation is prepared carefully at a high scientific level of presentation of the research topic and shows the author's excellent research comprehension on the dissertation topic addressed. I do not have any critical remarks on the dissertation.

I have the following questions to the dissertation's author:

- What is the dataset used for the experimental research presented in chapter four for forecasting the price of the digital currency bitcoin in US dollars?
- To what extent are the proposed approaches and hybrid algorithms for neural network training applicable to different time series? Are there any limitations and requirements, and if so what are they, for their application in different time series forecasting?

My recommendations to the author are to continue his research on the dissertation topic and to direct his efforts to the utilization of the developed models in practice in order to achieve direct applied results.

Conclusion

Based on the above said I consider the dissertation presented for review in the procedure for awarding the educational and scientific degree "Doctor" as fully corresponding to and fulfilling all the requirements of the Development of the Academic Staff in the Republic of Bulgaria Act and the Regulations on the Implementation of the Act as well as the Regulations for the Implementation of the Act in IICT–BAS. All of the minimum requirements for awarding the educational and scientific degree "Doctor" are satisfied with big over fulfilment of the requirements for the groups of indicators G. The dissertation is related to a relevant scientific area which has been highly targeted by considerable research efforts. The author has accomplished the dissertation goal and objectives. The dissertation results have scientific and applied contributions that are significant for both science and practice. The contributions obtained as a results of the dissertation studies are presented in numerous scientific papers that are published in scientific journals and presented at international research conferences thus making the dissertation results and the contributions available to the international scientific community.

Therefore, I am convinced of my positive assessment of the dissertation presented and propose to the honourable members of the Scientific Jury MSc. Eng. Petar Rosenov Tomov to be awarded the educational and scientific degree "Doctor" in the professional field 5.3 "Communication and Computer Engineering", scientific specialty "Communication Networks and Systems".

Date: 17.06.2022 **Reviewer:** На основание

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