

Marian Wysocki, PhD, DSc, Eng., university professor
Rzeszów University of Technology
Department of Computer and Control Engineering

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**Review of the doctoral dissertation of Mr. Rauzan Sumara, MSc., entitled
„Multiple Representation-Based Ensembles for Time Series Classification”**

prepared at the request of the Chairman of the Scientific Council of the Discipline of
Technical Information Technology and Telecommunications
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THE ISSUES OF THE DISSERTATION

Among the ever-increasing amount of available data, time series deserve special attention. They can be collected in a variety of situations, such as during business, biological, medical, and technical processes. Time series classification, mentioned in the title of the dissertation, is therefore of considerable importance as a crucial element of data analysis. In classification, building an ensemble of models that form the basis of classifiers is crucial. This stems from the expectation that combining a number of different models for the same classification task will yield improved prediction quality by compensating for the imperfections of these models. This requires appropriate techniques for creating and combining individual models. This problem is the basis of numerous studies. With respect to time series, an attractive approach has recently been grouping models using different data representation methods into an ensemble. Representations include feature-based representations, dictionary-based representations, where numerical time series are transformed into discrete sequences of symbols, interval-based representations, where features are generated from specific time segments of the series, and shape-based representations, where subsequences that distinguish the series are defined. The topic of this work is related to the aforementioned issues of creating and combining classification models. It is current and important, and due to its connection to data analysis and machine learning, it falls within the discipline of **technical information technology and telecommunications**.

THE STRUCTURE OF THE DISSERTATION

This 105-page thesis, written in English, consists of summaries in English and Polish, a table of contents, a list of figures and tables, six chapters, and a bibliography.

Chapter One, "*Introduction*", briefly outlines the thesis's subject matter, its scientific contribution, and structure, as well as a list of three publications closely related to the thesis, indicating the Candidate's participation as the first co-author.

Chapter Two, "*Time Series Classification Tasks*," provides basic introductory definitions to the problem of time series classification and describes the extensive UCR/UEA time series repository used in the experiments conducted by the Author. The repository was established at the universities of California, Riverside, and East Anglia and is widely used by researchers.

Chapter three, "*State-of-the-Art Overview*", analyzes the literature on research on the classification of one-dimensional time series. Approaches based on: (1) features, (2) dictionaries, (3) intervals, and (4) shapes are presented. Within these groups, known, representative methods are identified, respectively (1) Catch22, FreshPRINCE, Signatures, (2) TDE, WEASEL, (3) TSF, RISE, STSF, RSTSF, DrCIF, QUANT, (4) RSF, STC, RDST, respectively. Ensemble classifiers HC2, PF, TS-CHIEF, ROCKET, Arsenal, Hydra, and InceptionTime are also considered. All of the algorithms mentioned are reflected in the comparative analyses documented in subsequent chapters, comparing them with the Author's new proposals.

The fourth chapter, "*The MuRBE Structure*", focuses on the algorithms proposed by the Author. A new heterogeneous ensemble for time series classification, called MuRBE (Multiple Representation-Based Ensembles). The ensemble uses four base classifiers, one from each of the groups mentioned in Chapter 3. Groups (3) and (4) include DrCIF (diverse representation canonical interval forest) and RDST (random dilated shapelet transform), respectively. Classifiers from groups (1) and (2) are new proposals from the Author. The first method, ARFIMA-RF, combines the autoregressive, fractionally integrated moving average ARFIMA model with a random forest. The second, SAX-SGCNN, combines symbolic aggregation approximation SAX with layers of a recurrent GRU network preceding layers of a CNN. In the MuRBE algorithm, the Author proposed the use of fuzzy ranking, which has recently attracted attention due to its effectiveness in ensembles of different classifiers on different datasets, but has not been applied to time series data. According to this approach, to classify a new case, each independently trained base classifier generates probability estimates for each class. These probability estimates are then nonlinearly transformed using two functions with values in the interval $[0,1]$: (a) an exponential function representing a penalty that increases from zero as the deviation from probability 1 increases, and (b) a hyperbolic tangent function representing a reward that increases to unity as the probability of 1 is approached. The rank score corresponding to a particular probability estimate is determined by the product of the penalty and reward. The nature of the nonlinear functions used means that a higher probability estimate leads to a lower rank score. To obtain the final ensemble score, the ranking scores determined by the base classifiers are averaged for each class. A lower score indicates a more accurate prediction.

Chapter five, "*Experiments*", reports on an extensive comparative study of the proposed methods against known state-of-the-art algorithms. Forty datasets from the UCR/UEA repository were selected as datasets. Accuracy, balanced accuracy, and F1 score were evaluated. The results are elegantly presented using critical difference (CD) and multiple comparison matrix (MCM) diagrams. The CD diagram depicts the average ranks of each method across all datasets and indicates statistically insignificant differences in the rankings. MCM is a relatively new evaluation tool that uses average accuracy as a benchmark. The most important research results include: (i) CD diagram of average ranks and MCM matrix of average accuracy comparing the performance of the MuRBE ensemble with that of its component classifiers; (ii) CD diagrams and MCM matrices of accuracy, balanced accuracy, and F1 values of the MuRBE ensemble compared to classifiers not using ensembles; (iii) CD diagrams and MCM matrices as in (ii) comparing MuRBE with other ensemble methods; (iv) comparison of computational times when using the tested classifiers in the training and testing stages. MuRBE is shown to be significantly more accurate than the baseline classifiers and achieves competitive results compared to state-of-the-art methods on datasets from the analyzed repository. The Author declares that the software, prepared in Python, has been made available to researchers online.

Chapter six, "*Conclusions*", summarizes the research and discusses the limitations of the work, convincingly suggesting directions for further research.

The bibliography includes 70 representative items. Also included is a list of seven of the Candidate's publications unrelated to the dissertation, as well as an appendix tabulating the three main co-authored publications, each with a ministerial rating of 140 points, mentioned in Chapter 1.

EVALUATION OF THE DISSERTATION

The work addresses current and important problems in time series classification. The Author's main innovative achievements include:

- Proposing a novel, heterogeneous ensemble of classifiers MuRBE, covering diverse representation domains (based on features, dictionaries, intervals, and shapes) and combining predictions from different representations through a rank-based fuzzy ensemble structure.
- Proposing a unique feature-based time series classification method that uses parameters determined by the autoregressive fractionally integrated moving average (ARFIMA) for each time series.
- Introducing a novel dictionary-based time series classification system SAX-SGCNN, combining symbolic aggregation approximation (SAX) and deep learning using GRU recurrent network preceding convolutional layers.
- Extensive experimental studies on various datasets and domains, along with statistical analysis, demonstrating the advantages of the proposed methods.

The presented original results enrich existing knowledge in the field of time series classification methods.

Mr. Rauzan Sumara achieved the intended goal of his thesis by solving a clearly defined scientific problem. The work is theoretical and experimental in nature, and the experimental results are correctly analyzed. The author mastered the necessary theoretical foundations and demonstrated the ability to apply them to independently solve scientific problems. The new methods and experimental results presented in the thesis have both cognitive value and practical significance in the application of time series classification methods. They were the subject of three conference publications by the Candidate as the first co-author: *The Annual Pacific Asia Conference on Information Systems (PACIS 2024)*, *The 24th International Conference on Computational Science (ICCS 2024)*, and *33rd International Conference on Information Development (ISD 2025)*. Each of them received 140 points from the Ministry of Science and Higher Education. The thesis is interesting, well-structured, and carefully edited. This allows us to conclude that the Author has mastered the craft of writing scientific works. The references to publications and the valuable Chapter 3, which describes the issues of the dissertation in light of literature studies, indicate that the Author possesses the necessary bibliographic knowledge of the subject.

COMMENTS AND QUESTIONS

1. The work is carefully and correctly edited. There are some minor editorial errors: a reversal of the order of subsections 3.3.3 and 3.3.4, $d(s, x) = |s - x_{t, \dots, t+l}|$ instead of $d(s, x) = |s - x_{t, \dots, t+l-1}|$ on page 26, and the typo: MRM instead of MCM in the caption of Fig. 39.
2. A typical approach used in determining the prediction of an ensemble of classifiers is to maximize the average of the probabilities determined for a class by the base classifiers. The information fusion method described in the MuRBE algorithm can also be expressed similarly if the nonlinear transformation $f(p) = e(p) + h(p) - e(p)h(p)$ of the

probability p , where $e(p) = \exp\left(-\frac{(p-1)^2}{2}\right)$, $h(p) = \tanh\left(\frac{(p-1)^2}{2}\right)$, is used. The function f is increasing and takes values in $[0, 1]$. The formula for f is associated with the summation of probabilities. The resulting fusion results are, of course, consistent with those presented in the thesis. I suggest the Author present an interpretation in light of fuzzy logic.

3. Because classifiers make errors, we believe that diversity can be key to effective ensemble performance. We attempt to group sufficiently good classifiers that differ in their recognition errors. The MuRBE ensemble was built from four models based on different representations. Would it be reasonable in the future to formulate the task of building an ensemble selected from among many known models using optimization?
4. The experiments discussed in this work refer to univariate series. Does the Author have experience in applying his methods to multidimensional series and series that have different lengths in the training set?

SUMMARY

Mr. **Rauzan Sumara's** doctoral dissertation addresses an interesting and timely research topic. It provides an original solution to a scientific problem of practical importance with a documented novelty. It demonstrates the Candidate's general theoretical knowledge in the scientific discipline of **technical information technology and telecommunications**, as well as his ability to independently conduct research. **It meets the requirements of the applicable Act of July 20, 2018.**

I request the High Scientific Council of the Discipline of Technical Information Technology and Telecommunications of the Warsaw University of Technology to accept the work and allow the Candidate to publicly defend it.

Considering the broad scope of the research, the considerable practical usefulness of the solutions developed, and the co-authored publications at three recognized conferences (140 points from the Ministry of Science and Higher Education), I propose that the work be considered for recognition.

Rauzan Sumara