

REVIEW

on a dissertation thesis for obtaining scientific degree of “Doctor of Science”

Author of the dissertation thesis:

Assoc. Prof. PhD eng. Galya Nikolova Georgieva-Tsaneva

Title of the dissertation thesis:

Hybrid approaches for building a digital twin of heart rate variability

Scientific field:

5. Technica sciences

Professional field:

5.2 Electrical Engineering, Electronics and Automation

Scientific specialty:

02.21.02 Elements and Devices of Automation and Computing

Reviewer:

Prof. PhD eng. Nikolay Stoimenov, Institute of information and communication technologies at the Bulgarian Academy of Sciences

1. Relevance and significance of the problem addressed in this dissertation from both a scientific and applied scientific perspective

The present dissertation is dedicated to the development of an integrated methodological framework for the processing, analysis, simulation, and protection of cardiac signals. The central tenet of this framework is the utilisation of heart rate variability as a fundamental component in the development of a digital HRV twin, which is intended for utilisation in intelligent IoT-based biomedical systems. Cardiological signals (ECG, PPG, and HRV) represent a pivotal instrument in contemporary biomedicine and digital healthcare, as they furnish information pertaining to the condition of the cardiovascular system, stress levels, fatigue, and the risk of disease. The advent of wearable devices has precipitated the generation of voluminous data in real-world conditions, necessitating dependable methodologies for signal processing and analysis to eliminate noise, motion, and interference. Conventional methods have been shown to be inadequate in describing the intricate

dynamics of cardiac regulation. This underscores the necessity for the employment of nonlinear approaches, encompassing fractal, entropy, and chaotic analysis. The employment of simulation modelling of physiologically accurate cardiac signals is also of significant importance, aiding in the validation of algorithms, the training of artificial intelligence models, and the investigation of hard-to-observe physiological states. The relevance of this approach is also evident in the necessity to develop hybrid models that combine deterministic, stochastic, and chaotic components for a more complete reproduction of physiological dynamics. In this context, the concept of the HRV Digital Twin is emerging as a promising direction, representing a personalised approach.

2. Degree of knowledge of the state of the problem and creative interpretation of the literary material

The author has conducted a comprehensive review of current research and practical solutions in the field of processing, analysis, and modelling of cardiac signals (ECG, PPG, and HRV). The filtering of noise in electrocardiogram (ECG) and pulse pressure (PPG) signals poses a considerable challenge, particularly in portable devices.

The doctoral candidate evinces a profound comprehension of the prevailing state of the art through a meticulous and critical evaluation of contemporary scientific publications pertaining to the processing, analysis, modelling, and protection of cardiac signals. The extant literature on the subject is extensive and covers a wide range of classical and contemporary approaches, including linear and nonlinear methods, wavelet analysis, modal decomposition techniques, artificial intelligence methods, and deep learning.

A critical review of the scientific findings is particularly valuable in this context, as it has identified the existing limitations of the available solutions. These limitations include insufficient resistance to noise and artefacts, a lack of integrated simulation models, limitations in deployment in IoT environments, and insufficient protection of sensitive biomedical data. On this basis, the author clearly articulates the research gap and argues for the need to develop a new integrated methodological framework.

The creative interpretation of the literature is expressed in the integration of results from various scientific fields—signal processing, modelling, artificial intelligence, information security, and IoT technologies—into a unified concept for building a digital HRV twin. This demonstrates the ability to conduct critical analysis, synthesise knowledge, and formulate original research solutions.

3. Consistency between the chosen research methodology and the aim and tasks of the dissertation

The chosen research methodology is fully aligned with the stated objective and defined tasks of the dissertation. The integration of theoretical, experimental, and applied approaches is a distinctive feature, with classical mathematical methods being combined with modern AI-based techniques for the processing, analysis, modelling, and protection of cardiac signals.

The methodological framework is logically structured and consistently follows the set research tasks—from noise reduction and reliable detection of characteristic events in ECG and PPG signals, through the development of physiologically accurate simulation models and data protection mechanisms, to the analysis of HRV indicators and the creation of a digital twin of heart rate variability. The methods and algorithms employed facilitate the attainment of reliable outcomes in both controlled and real-world operating conditions in IoT and wearable systems.

It is important to note that the methodology is comprehensive and interdisciplinary in nature, which corresponds to the complexity of the research topic. The creation of the necessary conditions is pivotal for achieving the main objective of the dissertation and for obtaining scientifically sound and practically applicable results.

4. A brief analytical characterization of the nature and assessment of the reliability of the material upon which the contributions of the dissertation are based

The dissertation under review here comprises 250 pages, including 116 figures, 69 tables, and 235 cited sources, of which 28 pages are devoted to an analysis of the current state of the art in the field under consideration. The dissertation is organised into five chapters: introduction, conclusion, scientific contributions, applied scientific contributions, and applied contributions. The document comprises two lists: the first list is an abbreviation list, and the second is a list of the main symbols most frequently used in the equations and in the text. As demonstrated in Chapter 1, the literature review exhibits a profound comprehension of contemporary methodologies pertaining to the processing, analysis, modelling and security of cardiac signals. A comprehensive analysis of both classical and modern AI-based approaches is conducted, with a focus on their respective advantages and limitations when operating in real IoT and mobile environments. In Chapter 2, the developed methods are validated on real and synthetic PPG signals, using established quantitative metrics to assess processing quality and detection accuracy. The experiments demonstrate the reproducibility and robustness of

the results under various levels of noise and artefacts. This provides a foundation for concluding that the scientific results obtained are reliable and applicable in real-world conditions. As outlined in Chapter 3, simulation models are employed to reproduce the statistical, spectral and dynamic characteristics of real ECG, PPG and HRV signals. The original hybrid models that are proposed in this study combine Gaussian, fractal, stochastic, and AI-based approaches. The combination of these approaches ensures high physiological fidelity and controllability of the simulated data. The findings demonstrate the applicability of the models for the purposes of algorithm validation, training AI systems, and conducting personalised simulations. A robust simulation foundation has been established for the future development of a digital twin of heart rate variability. In Chapter 4, a range of proposed protection methods is presented, utilising well-established cryptographic and signal metrics. This facilitates an objective assessment of their effectiveness. The experimental findings demonstrate that the diagnostic value of the signals is maintained while concurrently ensuring a high level of security. This finding serves to substantiate the reliability of the experimental data that was utilised in this study, thereby validating the practical applicability of the solutions that were developed. In Chapter 5, a comprehensive methodological framework is proposed for the construction of an HRV Digital Twin. This framework integrates signal processing, intelligent analysis, simulation modelling and prediction of physiological states. New composite indices (FDTI, RDTI, and PDTI) have been developed to enable a reliable assessment of fatigue, recovery, and long-term adaptation in athletes. The results demonstrate a high level of sensitivity in distinguishing between physiological states and the potential for early detection of risk and autonomic dysregulation.

5. Scientific and scientific-applied contributions of the dissertation

The contributions of the dissertation are classified as follows:

SCIENTIFIC

1. A concept for the HRV Digital Twin has been formulated. This concept is intended to serve as a customisable and dynamic framework for modelling, interpreting, and predicting autonomic cardiac regulation.
2. Original methodologies for analysis and detection in PPG/ECG signals have been proposed, including a hybrid AI approach integrating wavelet representation, a CNN-LSTM architecture, and a temporal attention mechanism for detecting P-peaks in PPG signals.

3. New simulation models for HRV, PPG, and ECG signals have been developed, including hybrid and fractal-oriented solutions. Among these is the GMF–Rössler model, which combines morphological description and chaotic dynamics.

4. A region-adaptive principle for the protection of cardiological data has been formulated, in which cryptographic protection and watermarking are adapted to the diagnostic significance of the various signal segments.

SCIENTIFIC-APPLIED

1. A number of methodologies have been developed for the suppression of adaptive noise, the reliable detection of signals, and the extraction of intervals from pulse pressure and electrocardiographic signals. These methodologies have been validated under both real-time and power-constrained conditions.

2. Three fundamental HRV indices – FDTI, RDTI, and PDTI – have been developed to evaluate fatigue, short-term recovery, and long-term adaptation. These indices have been validated using data from athletes undergoing diverse training regimens.

3. A range of methodologies and frameworks have been developed for the secure processing of cardiac data. These include hybrid cryptography, watermarking, and mechanisms for traceability and authenticity. In addition, a multi-index method has been developed for the automatic real-time signalling of physiological risk.

APPLIED

1. The applicability of PPG-based interval series as a practical alternative to ECG in remote monitoring and wearable systems is demonstrated.

2. The capacity of the developed methodologies for implementation in telemedicine, sports science, personalised monitoring, and IoT-based systems is demonstrated, and an architectural framework for the future development of the HRV Digital Twin concept is outlined.

In view of the aforementioned points, it is my conviction that the results obtained, presented, and systematised herein constitute a contribution that is indisputable in terms of its relevance to the fields of biomedical engineering, digital health, biomedical signal processing, and the application of artificial intelligence methods for the analysis and modelling of cardiological data. The objective of this research is to develop intelligent systems for the monitoring, prediction and protection of physiological data. Concurrently, a methodological foundation is being established for the creation of a digital twin of heart rate variability in the Internet of Things (IoT) and telemedicine.

6. Assessment of the extent of the doctoral candidate's personal contribution to the research

I am acquainted with the research work of Assoc. Prof. Ph.D., Eng. Galya Nikolova Georgieva-Tsaneva, Of the 25 scientific publications presented, 14 are in journals with an Impact Factor (IF) and/or Science Citation Report (SJR) (6 in Q1, 2 in Q2, 4 in Q3, and 2 in Q4); 10 were presented at international and national scientific conferences, and 1 is a chapter in a monograph. A total of eight of the publications are individual works, and in 15 cases, she is the primary author. It is evident from the materials submitted for review that the candidate has made a significant contribution to the development and substantiation of the scientific results. It is reasonable to infer that the contributions presented are the result of the candidate's own work and her leading role in the research.

7. Evaluation of the publications related to the dissertation

The primary conclusions of the study have been disseminated through 24 scientific articles and a single chapter of a monograph. A total of sixteen publications have been indexed in international databases, of which fourteen are ranked by quartile. The author has been designated as the lead author in 15 of these publications and as the sole author in 8. A total of 71 citations of the publications related to this dissertation have been recorded, 52 of which are in SCOPUS and 19 in other journals.

8. Application of the findings of the dissertation in scientific and social practice

The results of this dissertation have significant potential for application in both scientific and social practice. The methodologies developed for the processing, analysis, modelling, and protection of cardiac signals have significant potential for application in the creation of intelligent health monitoring systems, telemedicine platforms, and wearable devices. The proposed models and integrated HRV indices provide new opportunities for the assessment of stress, fatigue, and recovery in sports medicine, preventive cardiology, and personalised healthcare. The potential of the simulation models and the HRV Digital Twin concept extends to future scientific research, the training of artificial intelligence algorithms, and the development of systems for predicting physiological states. The solutions for biomedical data security that have been developed also have important practical implications for protecting sensitive medical information in IoT and telemedicine environments.

9. Assessment of the abstract's compliance with the requirements for its preparation, as well as the adequacy of its presentation of the main applications and contributions of the dissertation

The abstract adequately reflects the essence of the dissertation, meets the requirements, and includes the main appendices and contributions.

10. Opinions, comments, and recommendations

I have no critical comments regarding the content of the dissertation.

11. Conclusion

Following a thorough analysis of the dissertation submitted for review, it is concluded that the document is in full compliance with the stipulated requirements of the Law on the Development of Academic Staff in the Republic of Bulgaria and the Regulations for its implementation. **I recommend that the distinguished academic jury award the author, Assoc. Prof. Dr. Eng. Galya Nikolova Georgieva-Tsaneva, the academic degree of "Doctor of Science."**

Date 01.06.2026 r.

MEMBER OF THE SCIENTIFIC JURY ..

(Prof. PhD Nikolay Stoimenov)