REVIEW

by Prof. DSc. Velislava Noreva Lyubenova
Institute of Robotics, Bulgarian Academy of Sciences
on a dissertation submitted for the award of the scientific degree of Doctor of Sciences (DSc)
by Assoc. Prof. Dr. Eng. Galya Nikolova Georgieva-Tzaneva
entitled:

"Hybrid Approaches for Building a Digital Twin of Heart Rate Variability"

Field of Higher Education: 5. Technical Sciences
Professional Field: 5.2 Electrical Engineering, Electronics and Automation
Scientific Speciality: "Elements and Devices of Automation and Computing"

By Order No. 50/20.04.2026 of the Director of the Institute of Robotics, Bulgarian Academy of Sciences, I was appointed as a member of the Scientific Jury for the procedure for awarding the scientific degree of Doctor of Sciences (DSc). In accordance with Minutes No. 1 of the first meeting of the jury, held on 21.04.2026, I was designated as reviewer of the dissertation. I have received all documents submitted by the candidate.

1. Brief Presentation of the Candidate

Assoc. Prof. Dr. Eng. Galya Nikolova Georgieva-Tzaneva graduated from the Higher Institute of Mechanical and Electrical Engineering – Varna in 1989 with a qualification in Electronics and Automation Engineering.

She was awarded the educational and scientific degree of Doctor (PhD) in 2016 at the Institute of System Engineering and Robotics of the Bulgarian Academy of Sciences.

Her research career at the Bulgarian Academy of Sciences began in 1990. Since 2010 she has held the academic position of Chief Assistant at the Institute of System Engineering and Robotics – BAS (currently the Institute of Robotics – BAS). During 2019–2021 she was a postdoctoral researcher under the National Programme "Young Scientists and Postdoctoral Researchers" of the Ministry of Education and Science. Since 2021 she has been an Associate Professor in the Medical Robotics Department of the Institute of Robotics – BAS, and since 2023 she has served as Head of that department.

2. Fulfilment of the Minimum National Requirements for the Award of the Degree of Doctor of Sciences

The submitted statement of compliance with the minimum national requirements clearly shows that Assoc. Prof. Dr. Eng. Galya Nikolova Georgieva-Tzaneva not only meets but substantially exceeds the requirements for the award of the scientific degree of Doctor of Sciences in Field of Higher Education 5. Technical Sciences.

Against a minimum threshold of 350 points, the candidate presents a total of 1,132.64 points — more than three times the regulatory minimum. Particularly outstanding are the results in indicator group G (424.64 points against a minimum of 100) and indicator group D (558 points against a minimum of 100).

These figures attest to high publication activity, significant scientific contribution, strong citation impact, and a sustained presence in the international scientific literature. They are

equally indicative of the scientific recognition and influence of the obtained results on the development of the relevant research field.

On the basis of the presented data, I conclude that the candidate fully meets and substantially exceeds the minimum national requirements and scientometric criteria for the award of the scientific degree of Doctor of Sciences.

Points by indicator group (Field 5. Technical Sciences)

Indicator Group	Indicator	Required Points	Candidate's Points
A	1. Dissertation for the award of the educational and scientific degree of Doctor (PhD)	50	50
B	2. Dissertation for the award of the scientific degree of Doctor of Sciences (DSc)	100	100
G	7. Scientific publications in journals indexed in internationally recognised scientific databases	40/n	307.98
	8. Scientific publications in non-indexed peer-reviewed journals or edited collective volumes	20/n	106.66
	9. Published chapter in a collective monograph (sole author)	10/n	10
Subtotal Group G		**100**	**424.64**
D	12. Citations and reviews in scientific journals indexed in internationally recognised databases or in monographs and collective volumes	10	520
	14. Citations and reviews in non-indexed peer-reviewed journals	2	38
Subtotal Group D		**100**	**558**
TOTAL		**350**	**1,132.64**

3. General Characteristics of the Dissertation

The dissertation addresses a timely and scientifically significant problem: the development of hybrid approaches for building a digital twin of heart rate variability (HRV Digital Twin). The

study is positioned at the intersection of intelligent biomedical signal processing, physiological process modelling, artificial intelligence, and digital healthcare.

The dissertation comprises 250 pages and contains 116 figures, 69 tables, and 235 references. It is structured into an introduction, five chapters, conclusions, and scientific contributions. The research is underpinned by 25 scientific publications that have received over 70 independent citations, attesting to the visibility and recognition of the results within the international scientific community.

In terms of content, the work is characterised by a clearly expressed interdisciplinary approach and a consistent research logic. The developed methods and models are unified by an overarching concept directed towards the analysis, modelling, and prediction of physiological states through heart rate variability.

I consider that the volume, structure, thematic scope, and scientific depth of the dissertation meet the requirements for the award of the scientific degree of Doctor of Sciences.

4. Relevance and Significance of the Research Topic

The relevance of the dissertation is determined by the growing need for reliable methods for processing, analysing, and interpreting physiological data in the context of digital healthcare, telemedicine, wearable devices, and IoT-based monitoring systems.

The scientific significance of the work derives from the role of heart rate variability as a sensitive indicator of autonomic nervous regulation, physiological stress, adaptive capacity, and cardiovascular risk.

The dissertation proposes an integrated approach combining signal processing, non-linear and fractal analysis, simulation modelling, and AI-based methods for the interpretation of physiological states.

Of particular significance is the aspiration to establish a concept for an HRV-based digital twin, which endows the research with both scientific and high scientific-applied value.

5. Analysis of Structure and Methodological Unity

The structure of the dissertation is logically organised and consistently subordinated to the stated scientific objective. The individual chapters do not constitute isolated research fragments; rather, they form an interconnected methodological sequence that progresses from problem analysis and the development of individual methods to their conceptual integration into a coherent scientific framework.

Chapter One is analytical and problem-oriented in character. It examines contemporary approaches to the processing, analysis, modelling, and protection of cardiological signals, identifies existing limitations and unresolved scientific problems, and on this basis justifies the need for an integrated approach to the analysis and prediction of physiological states.

Chapter Two is devoted to the preprocessing of ECG and PPG signals, noise suppression, and the detection of characteristic peaks. This part is of fundamental importance to the overall research design, as the reliability of all subsequent analyses and models depends directly on the quality of the input physiological data and the accuracy of the extracted temporal features.

Chapter Three addresses approaches to the simulation modelling of ECG, PPG, and HRV signals. Its scientific value lies in the ambition to model not only the statistical properties of the signals but also their non-linear, fractal, and dynamic characteristics, thereby providing a more realistic description of autonomic cardiac regulation.

Chapter Four is logically connected to the architecture of the digital twin and addresses issues of data security and protection. The inclusion of this topic is methodologically justified, since the operation of digital twin systems entails the continuous exchange, storage, and processing of sensitive medical information in IoT and telemedicine environments.

Chapter Five is synthetic in character and represents the culmination of the research. In it, the methods developed for signal processing, simulation modelling, HRV analysis, AI-based interpretation, and data protection are integrated into a unified conceptual framework for an HRV-based digital twin. This achieves a transition from individual methodological solutions to a comprehensive system for the assessment, interpretation, and prediction of physiological states, including fatigue, recovery, and risk.

I consider that there is a clearly expressed methodological unity and internal logical consistency among the individual chapters. The work progresses systematically from the resolution of specific scientific problems to their integration within an overarching conceptual framework — a hallmark of a dissertation that meets the requirements for the award of the scientific degree of Doctor of Sciences.

6. Scientific and Scientific-Applied Contributions

I accept in substance the scientific and scientific-applied contributions formulated by the author. I consider it appropriate to differentiate them according to their scientific significance, as they encompass results of varying degrees of theoretical depth, originality, and applied potential.

The scientific contribution with the highest level of generalisation is the development of a conceptual and methodological framework for an HRV-based digital twin, integrating the processes of acquisition, processing, modelling, analysis, and prediction of physiological states through heart rate variability. The concept is developed consistently throughout the dissertation and is synthesised in Chapter Five. A further significant scientific contribution is the integration of HRV analysis, fractal analysis, and AI-based methods for the unsupervised recognition of physiological states — an approach that goes beyond traditional linear HRV analysis and provides an interpretable basis for the construction of a digital twin. Also belonging to this group is the developed methodological framework that unifies biomedical signal processing, simulation modelling, AI interpretation, and data protection within a single architectural concept.

Of considerable scientific-applied value are the developed hybrid algorithms for PPG and ECG signal processing — in particular the DWT-CNN-LSTM architecture with a temporal attention mechanism for P-peak detection, achieving F1-scores of up to 0.92 — as well as the multi-factor wavelet-based method for adaptive noise suppression. Also belonging to this group are the three integral indices — FDTI, RDTI, and PDTI — designed for the assessment of fatigue, recovery rate, and physiological state prediction, validated on real data from athletes under various training regimes. The publication of these results in peer-reviewed journals with impact

factors, and the independent citations they have received in the international literature, provide further evidence of their significance.

The developed cryptographic models and watermarking schemes for the protection of cardiological data — including the proposed region-aware principle for adaptive protection calibrated to the diagnostic importance of individual physiological segments — are of engineering-applied character. Their value derives primarily from addressing practical data security challenges in IoT and telemedicine environments. The results are convincingly validated and demonstrate a high degree of clinical compatibility (PRD < 0.25% and SNR 31–40 dB), confirming their practical applicability.

In summary, the structure and hierarchy of the contributions reflect deepening scientific maturity — from the development of specific algorithmic solutions to the construction of a methodological framework and conceptual synthesis. It is precisely the capacity for systematic thinking, for integrating interdisciplinary approaches, and for unifying diverse methodological components into a coherent scientific concept that is the hallmark of a dissertation submitted for the award of the scientific degree of Doctor of Sciences.

7. Critical Remarks

Notwithstanding the indisputable scientific and applied merits of the dissertation, certain remarks and recommendations may be offered that do not diminish its value but rather outline opportunities for the further development of the presented research.

1. Although the literature review of methods for cardiological signal processing and analysis, simulation modelling, and AI-based approaches is comprehensive, the positioning of the proposed HRV Digital Twin concept relative to contemporary medical digital twin systems could be elaborated in greater detail. A clearer delineation of the elements of scientific novelty and originality with respect to current international developments would contribute to a more precise justification of the conceptual contribution of the dissertation.
2. The dissertation develops and validates a number of individual methods and models for the processing, analysis, simulation, and interpretation of cardiological data. Future research could profitably address their evaluation as a fully integrated HRV Digital Twin architecture. The conduct of unified comparative experiments on standardised public databases would allow for more precise benchmarking of the developed solutions against the current state of the art in the field.
3. A substantial part of the experimental studies is directed towards applications related to sports physiology, fatigue assessment, and adaptation to physical loading. Extending the validation to larger and more heterogeneous clinical populations would provide additional grounds for assessing the applicability and robustness of the proposed methods and indices across a broader spectrum of medical scenarios.
4. The presented AI-based models demonstrate high effectiveness in addressing specific tasks related to the analysis and interpretation of cardiological signals. In the context of future medical applications and intelligent monitoring systems, a more in-depth treatment of aspects related to the interpretability, explainability, and reliability of model decisions would be beneficial.

The remarks noted above do not in any way diminish the scientific value of the dissertation. On the contrary, they outline promising directions for the future development of the research and confirm the considerable potential of the proposed concepts, models, and methods for the advancement of modern systems for intelligent analysis and prediction of physiological states.

8. Compliance with the Requirements of the Academic Staff Development Act (ASDA) and its Implementing Regulations

Pursuant to Art. 12, para. 3 of the ASDA, a dissertation submitted for the award of the scientific degree of Doctor of Sciences must contain theoretical generalisations and solutions to major scientific or scientific-applied problems that constitute a significant and original contribution to science.

I consider that the presented dissertation satisfies these requirements. Both original scientific results and solutions to significant scientific-applied problems are present. The work constitutes an independent and conceptually completed scientific study containing significant scientific and scientific-applied results unified within a single methodological framework.

The presented results demonstrate an independent scientific direction, an interdisciplinary approach, and a high degree of scientific synthesis. I therefore conclude that the dissertation meets the requirements of the ASDA and its Implementing Regulations for the award of the scientific degree of Doctor of Sciences.

CONCLUSION

The presented dissertation represents a significant, independent, and completed scientific study with original scientific and scientific-applied contributions.

The work demonstrates high scientific competence, an interdisciplinary approach, sound methodological grounding, and the capacity for scientific synthesis. I particularly value the conceptual unification of the developed methods and models into a single framework for an HRV-based digital twin.

I conclude that the dissertation fully meets the requirements of the Academic Staff Development Act, its Implementing Regulations, and the criteria for the award of the scientific degree of Doctor of Sciences.

On the basis of the foregoing assessment, I give a positive evaluation of the dissertation and confidently recommend that the respected Scientific Jury award Assoc. Prof. Dr. Eng. Galya Nikolova Georgieva-Tzaneva the scientific degree of Doctor of Sciences.

Date: 08.06.2026

Sofia

Reviewer: .....