

Prof. Paweł Skruch

Department of Automatic Control and Robotics

AGH University of Krakow

Adam Mickiewicz Avenue 30/B1, 30-059 Kraków, Poland

E-mail: pawel.skruch@agh.edu.pl

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PRZEWODNICZĄCY RADY DISCYPLINY
Automatyka, Elektronika, Elektrotechnika
i Technologie Kosmiczne

prof. dr hab. inż. Wojciech Szelaąg

REVIEW OF DOCTORAL DISSERTATION

by Rafał Mateusz Sobański

entitled „Cooperative distributed navigation for wheeled mobile robots using the Vector Field Orientation approach under time constraints”

I. Basis for Preparing the Doctoral Dissertation Review

This review concerns the doctoral dissertation of M.Sc. Eng. Rafał Mateusz Sobański entitled “Cooperative distributed navigation for wheeled mobile robots using the Vector Field Orientation approach under time constraints”, submitted in the discipline of Automation, Electronics, Electrical Engineering and Space Technologies. The dissertation was supervised by Prof. Maciej Michał Michałek and Prof. Michael Dofort.

I prepared this review at the request of Prof. Wojciech Szelaąg, D.Sc., Ph.D., Eng., Chair of the Discipline Council for Automation, Electronics, Electrical Engineering and Space Technologies, acting pursuant to Resolution No. 135/2024–2028 of the Discipline Council for Automation, Electronics, Electrical Engineering and Space Technologies of Poznań University of Technology, dated 10 March 2026.

II. Evaluation of the Originality of the Research Problem Addressed in the Dissertation and Its Significance for the Development of the Discipline

The research problem addressed in the dissertation concerns the development of control algorithms for nonholonomic mobile robots and distributed multi-robot systems composed of nonholonomic robots. The proposed control methods are based on the Vector Field Orientation methodology. The developed algorithms are intended for unicycle-type mobile robots, whose motion is described using kinematic models. The proposed approach takes into account both control input constraints and task execution time constraints. The dissertation employs the concept of fixed-time stability, according to which the system errors converge to zero within a finite time whose upper bound is specified a priori by a predetermined constant. Two control problems for a nonholonomic mobile robot are considered in the dissertation: point stabilization and path following along a non-parametrized reference path. For the nonholonomic multi-robot system, control algorithms are developed to enable the robots to establish and maintain prescribed formations.

Issues related to the control of nonholonomic robots, taking into account constraints imposed on control inputs and task execution time, constitute an important aspect of modern autonomous systems. They are directly related to ensuring the safe, efficient, and timely execution of tasks associated with robot motion. In practical applications, one of the important constraints is the available energy of the power supply system. Mobile robots are typically powered by batteries with limited capacity; therefore, the control strategy, and in particular the magnitude and temporal characteristics of the control inputs, can have a significant impact on energy consumption and, consequently, on the robot's autonomous operating time. At the same time, in many autonomous system applications, particularly those operating in real time, the time required to reach a desired state or complete a specific task is of critical importance. Therefore there is a need to design control algorithms that, on the one hand, account for the physical and energy constraints of the actuation system and, on the other hand, ensure task completion within the required time. Incorporating these constraints at the control algorithm design stage makes it possible to develop solutions that are not only theoretically correct but also energy-efficient and suitable for implementation in real-world systems.

In summary, I conclude that the research topic addressed in the dissertation is timely and relevant, both from the perspective of industrial needs and from the perspective of the development of the discipline of Automation, Electronics, Electrical Engineering and Space Technologies.

III. Evaluation of the Correctness and Completeness of the Research Objectives and Hypotheses

The author of the dissertation formulates the following research hypothesis: „The Vector Field Orientation (VFO) methodology enables the development of a control algorithm for a single nonholonomic mobile robot and its decentralized extension for a multi-robot system, that guarantees satisfaction of time constraints imposed on the execution of a selected motion task defined for nonholonomic mobile robots in the presence of control input constraints”. The hypothesis is correct from both linguistic and logical perspectives. It assumes the possibility of developing a control algorithm for a single nonholonomic mobile robot and extending it to a decentralized multi-robot system, while taking into account constraints on task execution time and constraints imposed on the control inputs. The formulated hypothesis can be verified both theoretically, through an analysis of the properties of the developed algorithms and appropriate mathematical proofs, and experimentally, through simulation studies and experiments involving real robotic systems.

I therefore conclude that the research hypothesis formulated in the dissertation is logically and substantively sound.

IV. Evaluation of the Structure of the Dissertation

The dissertation consists of an introduction, four main chapters, and a bibliography. At the beginning of the dissertation, the author provides a detailed list of the symbols and notations used throughout the work, which significantly facilitates its reading and enables the reader to readily identify the meaning of individual variables and parameters.

The introductory chapter presents the motivation for undertaking the research topic, formulates the objectives of the dissertation and the research hypothesis, and provides an overview of the structure and content of the individual chapters.

Chapter 1 introduces the fundamental concepts and issues related to the research topic addressed in the dissertation and provides a review of the current state of knowledge in the field of control of nonholonomic mobile robots and multi-robot systems.

Chapters 2 and 3 present the main scientific contributions of the dissertation. Chapter 2 describes the methodology for designing control algorithms based on the Vector Field Orientation methodology for a single nonholonomic robot. Chapter 3, in turn, focuses on the development of control algorithms for a distributed multi-robot system composed of individual nonholonomic robots. Each of these chapters presents the formulation of the considered control problem, the proposed solution together with its analytical justification and mathematical proofs, followed by the results of experimental studies conducted both in a simulation environment and using real robotic systems.

Chapter 4 provides a summary of the most important results obtained in the dissertation and identifies potential directions for future research and further development of the proposed methods.

The final part of the dissertation is the bibliography, which includes the publications and other sources consulted by the Author in preparing the dissertation.

In summary, I conclude that the structure of the dissertation is logical and coherent and appropriately reflects the course of the research process, including the formulation of the research problem, the development of methods for its solution, their theoretical analysis, and the validation of the obtained results.

V. Evaluation of the Applied Research Methodology and Research Methods

The starting point for the design of the control algorithms described in the dissertation is the Vector Field Orientation methodology. Within this methodology, the first step is to define a desired vector field in the workspace that specifies the required direction of robot motion as a function of its current position. Subsequently, a control algorithm is designed to appropriately regulate the robot's linear velocity and orientation so that its motion follows the direction defined by the vector field while taking into account the constraints arising from the nonholonomic nature of the system.

The fixed-time stability analysis is based on the Lyapunov method, in which the existence of an appropriately selected positive definite Lyapunov function is established. Its time derivative along the trajectories of the closed-loop system is then analyzed, and it is shown to satisfy a specified differential inequality. This makes it possible to analytically estimate an upper bound on the convergence time of the errors to zero, independently of the initial conditions.

The theoretical results obtained are subsequently verified through computer simulations and experiments conducted using real mobile robots. This combination of theoretical analysis, simulation studies, and experimental validation enables a comprehensive assessment of the correctness and practical applicability of the proposed control algorithms.

The research methodology presented in the dissertation is appropriately selected for the formulated research problem, providing a basis for both the theoretical analysis of the properties of the developed algorithms and their practical validation. Moreover, the methods employed are widely used in the literature for the analysis and solution of similar control problems.

VI. Evaluation of the Theoretical Knowledge Presented in the Dissertation

The author demonstrates a very high level of theoretical knowledge in the design of advanced control algorithms for dynamic systems. Particular attention should be given to the author's meticulousness, consistency, and coherence in the use of mathematical notation, as well as the precision with which the problems under consideration are formulated. The theorems and lemmas are formulated correctly and unambiguously, while the proofs are presented with due rigor and in accordance with the standards expected of scientific work in the field of control theory. The author demonstrates a strong command of the mathematical apparatus, particularly Lyapunov methods, which are effectively employed to analyze stability and substantiate the properties of the proposed control algorithms.

The author's ability to combine formal mathematical analysis with the practical aspects of control algorithm design also deserves particular attention, including the consideration of control input constraints and requirements concerning task execution time. The analyses done by the author demonstrate a very good knowledge of both classical and advanced control theory methods, as well as the ability to apply them appropriately to the solution of complex control problems involving nonholonomic robots.

In the context of the research problem addressed, I assess the level of theoretical knowledge presented in the dissertation as very high. The formulation of the problems, the level of the mathematical apparatus employed, the correctness of the analyses conducted, and the manner in which the results are presented meet the standards expected of high-quality scientific work published in peer-reviewed journals in the fields of automation, control theory, and robotics.

VII. Evaluation of the Doctoral Candidate's Ability to Properly Present the Obtained Research Results.

The author of the dissertation places appropriate emphasis on the rigorous and multifaceted verification of the research hypothesis and on the achievement of the formulated research objectives. The conclusions drawn from the analysis of the theoretical and experimental results obtained are presented in a clear, concise, and logically structured manner, directly relating to the stated research objectives. Particular attention should be given to the fact that the author frequently provides additional remarks and comments concerning the presented results and main findings, which contribute to a better understanding of the results, clarify important aspects, and place them within a broader research context.

The results of the experimental studies, conducted both in a simulation environment and using real mobile robots, are presented with great care and attention to detail. The description of the experiments provides the necessary information regarding the underlying assumptions, experimental conditions, and parameters used to evaluate the obtained results. This not only enables an assessment of the correctness of the proposed solutions but also facilitates their reliable validation and comparison with the results obtained through analytical methods.

In summary, I conclude that the doctoral candidate has demonstrated a very high level of proficiency in presenting research results accurately and in preparing clear and technically sound scientific text.

VIII. Evaluation of the Formal Aspects of the Dissertation

The doctoral dissertation has been written carefully and is correct in terms of language and style. The individual chapters are concise and well balanced in terms of length, and their content focuses on the key issues relevant to achieving the research objectives. Their sequence is appropriate and logically structured. The author uses consistent and correct mathematical notation, demonstrating great attention to detail. In particular, variables are denoted using italic font, while vector and matrix quantities are denoted using bold font. Units of physical quantities are written in upright font and comply with the conventions of the International System of Units (SI).

The figures have been prepared carefully, are of appropriate quality and resolution, and include clear and adequate descriptions. Their graphical presentation facilitates the understanding of the issues discussed and the research results presented.

A certain difficulty in reading the dissertation is caused by the relatively large number of symbols and notations used throughout the work. In some parts of the text, the reader needs to refer to the list of symbols provided at the beginning of the dissertation to recall the meaning of particular notations. In addition, in some mathematical expressions, it is not always clear which symbols represent variables and which represent parameters or constants.

In summary, I conclude that the dissertation has been prepared and edited correctly in terms of its formal, linguistic, and editorial aspects, and that the manner in which the content is presented meets the standards expected of scientific work.

IX. Evaluation of the Literature Review and the Use of Relevant Scientific Sources

The bibliography comprises a total of 143 references, including primarily articles published in scientific journals, as well as conference papers and books. The vast majority of the references are relatively recent, with publications from the last 15 years clearly predominating. The selection of sources is appropriate to the subject of the dissertation and covers both fundamental works and recent research results related to the control of nonholonomic mobile robots and multi-robot systems.

Among the cited references are also publications [85] and [115]–[120], of which the doctoral candidate is a co-author. The dissertation also takes into account research conducted by scientists from the institutions where the research underlying the dissertation was carried out, indicating the author's familiarity with the local research context and the appropriate positioning of the obtained results within the existing body of scientific knowledge.

From an editorial perspective, the bibliography is prepared in a consistent and uniform manner. All references contain the basic bibliographic information required by the adopted citation style, which facilitates the identification of the sources used. **I assess the selection, currency, and presentation of the literature positively and consider them appropriate for a doctoral dissertation.**

X. Identification of the Original Scientific Contributions

In pursuing the research objectives formulated in the dissertation, the author has obtained new, original, and distinctive results, which include the following:

- (1) Design, development and verification of a control algorithm based on the Vector Field Orientation methodology that ensures a nonholonomic unicycle-type mobile robot reaches the desired configuration within a finite, a priori bounded time, while accounting for constraints imposed on the control inputs and providing an analytical estimate of the settling time (Theorem 1);
- (2) Design, development and verification of a control algorithm based on the Vector Field Orientation methodology that ensures that a nonholonomic unicycle-type mobile robot reaches the desired path within a finite time and subsequently follows the path at a constant longitudinal velocity, while accounting for constraints imposed on the control inputs (Theorem 2);
- (3) Design, development and verification of an observer for a distributed multi-robot system composed of unicycle-type mobile robots, enabling the estimation of the consensus equilibrium state within a finite, a priori bounded time, independently of the initial conditions (Theorem 3);
- (4) Design, development and verification of a control algorithm for a distributed multi-robot system composed of unicycle-type mobile robots, utilizing a reference configuration estimated by an observer and ensuring convergence of the system to the desired configuration within a finite, a priori bounded time, independently of the initial conditions (Theorem 4);
- (5) Design, development and verification of a control algorithm for a distributed multi-robot system composed of unicycle-type mobile robots, ensuring convergence of the system to the desired formation within a finite, a priori bounded time, independently of the initial conditions (Theorem 5).

XI. Comments and Remarks

After reading the doctoral dissertation, the following general comments arise:

- (1) The research hypothesis formulated in the dissertation suggests that the developed control algorithms take into account constraints imposed on task execution time. However, the results presented indicate that the proposed algorithms ensure that the desired equilibrium state is reached within a finite time, for which an upper bound can be analytically estimated. This does not, however, imply that the obtained convergence-time estimate takes into account external requirements concerning the maximum task execution time specified by the system designer. In other words, ensuring convergence within a finite time is not equivalent to guaranteeing compliance with an arbitrary prescribed time constraint. In this context, the statement that the proposed algorithms “take into account time constraints” appears to be too strong and would require further clarification. A more appropriate statement would be that the algorithms ensure convergence to the desired state within a finite time and allow for an analytical estimation of the upper bound on the convergence time. If the author’s intention is to genuinely incorporate a time constraint imposed by the system designer, it would additionally be necessary to demonstrate that the controller parameters can be selected in such a way that the estimated convergence time does not exceed the prescribed task

execution time. In such a case, it would be justified to state that the time constraint is explicitly taken into account in the control design process.

- (2) The vector fields proposed in the dissertation and the resulting control algorithms are characterized by a rather specific and complex mathematical form. Assuming that the presented methodology can also be applied to other robotic platforms, it would be useful to provide a more detailed explanation of the motivation behind the adopted mathematical form of the vector fields and the resulting control laws. In particular, it would be interesting to indicate which properties of this construction are essential for achieving the required stability and convergence properties, and to what extent the adopted formulation is related to the specific characteristics of the kinematic model of the unicycle-type robot. Such an explanation would make it possible to better assess the potential for generalizing the proposed approach to other classes of robots and their dynamic models.
- (3) The control algorithm design methodology presented in the dissertation exhibits certain conceptual similarities to sliding-mode control methods, particularly those that ensure reaching the sliding surface within a finite time. In both approaches, an important role is played by appropriately shaping the error dynamics and ensuring its convergence within a finite time. Therefore, it would be valuable to provide a more comprehensive discussion of the proposed methodology in relation to sliding-mode control and to identify the fundamental similarities and differences between these approaches, particularly in terms of stability conditions, convergence time, control input constraints, and potential undesirable phenomena such as chattering. Such a comparative analysis would help to better highlight the original features and advantages of the proposed approach.
- (4) From the perspective of practical applications of mobile robot control, predictive control methods, particularly Model Predictive Control (MPC), constitute an important point of reference, as they allow constraints imposed on system states and control inputs to be taken into account directly in the control design. Therefore, a comparison of the proposed methodology with the MPC approach, both in terms of theoretical properties and the results obtained in simulation or experimental studies, would constitute a valuable addition to the dissertation. Such an analysis would also make it possible to better assess the trade-off between computational complexity, guaranteed convergence time, the ability to handle constraints, and the practical implementation of the proposed control algorithms.
- (5) Each real-world mobile robot is characterized by its own dynamics, whose significance may vary depending on the type of platform, its parameters, and the operating conditions. In some applications, the effects of dynamics may be negligible, whereas in others, for example at high operating speeds, during rapid trajectory changes, in the presence of significant inertial forces, or when the actuator dynamics are limiting, they may play a critical role in the quality and stability of the control system. The control algorithm design methodology presented in the dissertation is based exclusively on kinematic models of the robots. This naturally raises the question of the extent to which the proposed control laws can be applied to platforms for which the dynamics of motion cannot be neglected. In particular, it would be of interest to identify the conditions under which the difference between the kinematic model and the actual dynamic model remains sufficiently small for the proposed control laws to retain their assumed properties. It would also be valuable to investigate whether and how the proposed

methodology could be extended to incorporate the robot dynamics, for example by introducing an additional control layer or appropriately modifying the control law. The dissertation presents experimental results obtained using real robotic platforms, which confirm the practical feasibility of implementing the developed algorithms. However, considering the values of the analyzed control inputs, motion velocities, and state variables, it may be assumed that, under the operating conditions considered in the experiments, the influence of the robot dynamics was relatively small and did not significantly affect the performance of the proposed algorithms. Therefore, a valuable extension of the dissertation would be an analysis of the robustness of the proposed approach to significant dynamic effects, for example by conducting experiments at higher velocities, involving more dynamic maneuvers, or using models that account for inertia and actuator dynamics.

XII. Overall Evaluation and Final Conclusions

I conclude that the author of the doctoral dissertation has demonstrated the validity of the research hypothesis formulated in the dissertation. To this end, the author employed an appropriate system approach, enabling a comprehensive analysis and understanding of the research problem, and subsequently selected appropriate research methods, including, in particular, the Vector Field Orientation methodology and the Lyapunov functional method. The adopted research framework was properly designed and implemented, and the research methodology was consistent with the principles and standards generally accepted for scientific research. The theoretical results obtained were further validated through simulation and experimental studies, enabling a comprehensive assessment of the developed methods. Thus, the author has demonstrated the ability to independently formulate and solve scientific problems and has confirmed his qualifications and aptitude for obtaining the doctoral degree.

The reviewed doctoral dissertation by M.Sc. Eng. Rafał Mateusz Sobański meets the requirements set out in Article 187 of the Act of 20 July 2018 – *Prawo o szkolnictwie wyższym i nauce* (Dz. U. z 2022 r. poz. 574 z późn. zm.). In particular, the doctoral dissertation demonstrates the candidate's general theoretical knowledge in the discipline of Automation, Electronics, Electrical Engineering and Space Technologies, as well as his ability to conduct scientific research independently. Furthermore, the subject matter of the doctoral dissertation constitutes an original solution to a scientific problem.

I recommend that the dissertation be accepted and admitted for public defense.

Taking into account the very high scientific quality of the dissertation, the originality and scientific value of the results obtained, as well as the high standard of the theoretical analyses and experimental studies, which meet the standards expected of high-quality publications in international scientific journals, I hereby recommend that the doctoral dissertation be awarded a distinction.

Paweł Skruch