WYDZIAŁ AUTOMATYKI, ROBOTYKI I I ELEKTROTECHNIKI POLITECHNIKA POZNAŃSKA

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Review of the doctoral dissertation of Rafał Sobański, M.Sc., Eng., "Cooperative distributed navigation for wheeled mobile robots using the vector fields orientation approach under time constraints."

Legal basis:
The review was commissioned by the Chairman of the Scientific Council of the Automation, Electronics, Electrical Engineering, and Space Technologies Discipline at the Poznań University of Technology, Prof. Wojciech Szeląg, Ph.D., Eng., in accordance with Council Resolution No. 138/2024-2028 of June 23, 2026, appointing me as a reviewer in the doctoral dissertation of Rafał Sobański, M.Sc., Eng.

1. General characteristics.
Robot control is a specific subset of classical control theory tasks, defined by the specificity and practicality of the models used. Quite often, a robot model is simplified to a holonomic model, seeking interesting results by complicating the environment by limiting the space allowed by obstacles.

Controlling non-holonomic robots is a difficult and multifaceted task, even without environmental obstacles (controlling to a point, following a path or trajectory) due to the inability to move directly in arbitrary directions. Additional requirements, often motivated by practical reasons (e.g., respecting control constraints), make its satisfactory solution even more difficult. There are many techniques, of which the VFO methodology is important because it offers an intuitive and geometrically well-understood method for achieving control goals by appropriately directing the robot's coordinates towards the target, and by effectively applying the technique resulting from the Lyapunov's second principle, as well as formally provable results.

This dissertation undertakes the ambitious project of expanding the application of the VFO methodology to two planning tasks with guaranteed upper convergence time and taking into account control constraints. The robot model is a basic nonholonomic robot considered in the literature, a unicycle, commonly used in practice. The VFO methodology has been present at works of Poznań scientists for many years, and the dissertation significantly expands the scope of considerations not only for a single robot, but also for a distributed multi-robot system with a diverse topology of inter-robot information exchange. The thematic scope of the dissertation lies entirely within the discipline of Automation, Electronics, Electrical Engineering, and Space Technologies.

2. Form and Composition of the Dissertation.

The dissertation, written in English, contains 106 numbered pages in Arabic, preceded by an English abstract and summaries, along with their extended versions in Polish and French, along with bibliography concerning the abstract section and acknowledgments. The text proper is preceded by a table of contents and a very extensive (six-page) list of notations used in the dissertation. The dissertation consists of five numbered chapters, preceded by an unnumbered chapter. The unnumbered chapter contains the motivation for the dissertation, an explanation of the main concepts, a justification of the practicality of the undertaken research, and a list of three objectives serving to justify the subsequently formulated thesis. This thesis states that the VFO (velocity field orientation) methodology enables the design of control algorithms for a non-holonomic robot and its cooperative group (exchanging available information) in a decentralized manner while maintaining practically important constraints regarding convergence time and control constraints for selected motion planning tasks. Next, the author's original contributions are specified and the content of each section of the dissertation is briefly described. The chapter is complemented by a list of co-authored works on which the dissertation is based, including two publications in high-profile journals and five presentations at conferences of established international and national standing.

Chapter 1 is introductory in nature, defining the types of stability, with particular emphasis on stability over finite or fixed time. A series of lemmas from the literature and co-authors introduces upper bound estimates of the convergence time to the equilibrium point of the analyzed system. The VFO methodology is presented with reference to the basic robot of the dissertation, a unicycle, emphasizing the importance of the key auxiliary orientation vector as the orientation field angle expressed in the global coordinate system. The final subsection cites literature and algebraic methods for defining the topology of collaborative robots, including literature-based laws for establishing consensus between robots sharing information. The discussion of Chapter 1 is set against a broad background of the literature. This is followed by two extensive main chapters of the dissertation.

Chapter 2 proposes control laws for a single unicycle robot for two classical tasks: reaching a point in configuration space and following a path in that space, provided that control constraints are satisfied, in the form of fixed constraints on their maximum amplitudes, and with an estimated upper bound on achieving a stable equilibrium state of a suitably defined error signal (i.e., completing motion planning tasks). The VFO methodology, which involves defining a convergence field and linking it with appropriate laws to closed-loop control, applied to a specific unicycle model enables the achievement of analytical and deep theoretical results regarding the estimation of the upper convergence time independent of the position of the initial conditions (although within a given region). The proposed method of proof consists in proposing control laws that first guarantee the proper convergence of the auxiliary orientation, then of the positional coordinates, and consequently also of the robot's orientation. The difference between point-based stabilization and non-parametric path tracking tasks lies in the appropriate definition of error. The orientation part is practically identical for both tasks, but the positional part differs significantly. For the point-based case, error is classically understood, while for the tracking task it is defined as the distance from the zero value of the layer function. For the point-based task, the author's a priori estimate of the upper settling time is particularly interesting, as for the tracking task it can only be determined a posteriori. The algorithmized theoretical considerations are illustrated with arithmetic simulation and experimental examples performed on the mTracker laboratory robot, confirming the theoretical considerations and providing some insight into the conservativeness of the upper bound estimates of the convergence time. Although the subject of this dissertation is not the study of the robustness of the formulated algorithms, the author has made some observations demonstrating the possibility of their application even in the presence of various types of inaccuracies.

In Chapter 3, the problem is generalized and complicated by considering a multi-robot system whose goal is to achieve formation (i.e., the appropriate arrangement of robots relative to an unspecified central point and a predetermined common orientation). In Section 3.2, the system control problem is formulated, along with mathematical inequalities used to estimate upper bounds. In Section 3.3, the construction of a decentralized observer system (each robot has its own observer) is proposed as a method for achieving formation, as well as a law for the change of estimates described by a vector between the current state and a hypothetical target state. The goal is for all robots to achieve convergence of estimates. Through an interesting formulation of the error function, taking into account informational interactions between robots, convergence of the error in a fixed time is achieved, first for the inter-robot communication topology described by an undirected graph, and then (computationally somewhat more complex) by a directed graph. The convergence proofs utilize the Lyapunov function technique, interestingly symmetrizing it for the case of a topology described by a directed graph. In Section 3.3.2, control laws for robots are formulated, similarly to those for the single-robot case, but taking into account estimates rather than actual data, demonstrating similar properties as for the single-robot problem in Section 2.2.2. Section 3.3.3 illustrates the theoretical considerations using the example of a five-robot system, and the next section indicates potential possibilities for avoiding collisions between robots and static obstacles by changing design parameters (and certainly detecting the possibility of such collisions).

Subsection 3.4 presents an alternative method for obtaining a formation using the concept of consensus. This time, individual position error vectors take into account not only the position of a specific robot, but also the unknown (target) position relative to the formation's center point and the positions of robots incident to the given robot. Orientation errors are relative to the established target orientation of the entire formation. The proposed control law, based on the VFO methodology, guarantees convergence to a stable formation within a fixed time, and the convergence proof is performed step-wise (convergence of the auxiliary orientation, convergence of positional coordinates, convergence of orientation). One aspect not present in single-robot systems is the need to propose a method for synchronizing the scaling functions for all robots after a certain transition time to avoid undesirable system behavior. The content of this sub-chapter is complemented by simulation examples and experimental results for a four-robot system, confirming the expected behavior of the system, consistent with the theory.

Chapter 5 summarizes the dissertation. It lists the main achievements of the dissertation, presents the sources of the conservativeness of the achieved upper bounds on the task completion time, and formulates plans for the future.

The bibliography concludes the dissertation and contains contemporary literature on the subject, carefully selected both in terms of quantity and thematic content.

3. Original Achievements

I consider the author's original achievements to be:

1. Using literature concepts (stability in finite/fixed time) and adapting them to the case

of a system of nonholonomic unicycle-type mobile robots to propose control laws that enable achieving stronger conditions than those found in the literature regarding the upper bound on the time to reach the target steady state (in the environment). This utilizes the locality of the allowable initial conditions while maintaining practically important control constraints.

2. Providing formal proofs (an impressive number of theorems) describing guaranteed properties for the task of stabilization to a point or tracking a given path in a non-parametric manner for a single robot using the VFO methodology.
3. Extending the applicability of the VFO paradigm to the case of multiple homogeneous unicycle-type robots, taking into account practically important (especially for mobile robots) constraints on control amplitudes.
4. Algorithmization of theoretical results and verification of the performance of the proposed controllers based on them, both in simulation and in practice on mTracker robots.
5. Presentation of two original methods (based on estimation and the concept of consensus) for creating an initial formation, based on the VFO methodology, for a distributed multi-robot system. This includes the control laws of individual robots, taking into account their relationships with neighboring robots, and proof of convergence to a formation characterized by an appropriate arrangement of the robots' mutual positions and their established orientation.

4. Remarks, comments, questions.

General:

1. For the unicycle model, the natural configuration space is $\mathbb{R}^2 \times \mathbb{S}^1$ (and not, for example, $\mathbb{R}^3$). Did this cause any problems? For example, the transition with an angle between the $-\pi$ neighborhood and the π neighborhood?
2. The *finite-time stability* concept 5_3 states that after time $t_s(z_0)$, the system is permanently at equilibrium. However, comments $8_2 - 9^2$ state that the system converges to zero at this time. Please explain.
3. The two-stage procedure for obtaining constrained controls assumes scaling with respect to the locally relative (relative to the maximum allowable) maximum value of the controls. While nominal controls (unconstrained) can (are) continuous with the first derivative, at points where scaling is active (control saturates), the continuity of the control derivative may not be preserved. If so, what negative consequences might be realistically observed?
4. For the path tracing problem using the level-set method, the examples given this set in the form of a loop (this is how sub-manifolds are classically defined). Is it possible to apply the proposed approach to the case where this set is not a loop, e.g., a semicircle?
5. The dissertation assumes the most common constraints on controls (the feasible set is an appropriately dimensional cuboid). What difficulties, within the adopted paradigm, should be expected if we assume, practically interesting, constraints on the total energy of the controls in the form $\sum_{i=1}^{n} u_i^2 = M$?
6. Is it possible to determine (at least heuristically) what the relationship is for a multi-robot system between the (initially unknown, but known after the planning phase) target position of the formation center and the robot configurations in their initial state?
7. A practical complication present in virtually all navigation methods – especially in multi-

robot systems – seems to be the need to monitor the configuration of individual robots in the global coordinate system.

Technical and editorial:

- It was worth adding a definition of the radial function, page 6, (as invariant under rotations) and commenting on the meaning of the notation $V(\|\boldsymbol{z}\|)$, since formally the argument of the function V is a vector from the subset $\mathbb{R}^n$, not a scalar (as the notation suggests).
- The structure of the set $\mathcal{V}$, 5^{16}, is defined as connected. Is anything more assumed about this set? (open/closed?)
- 5_{11}: $f(0) = 0 \rightarrow f(\mathbf{0}) = \mathbf{0}$
- A few typos: 7_{13} continous, 9_{17} homogeneity, 44_2 sine, or 39^8 repetitions.
- At the end of the proof on page 8, the monotonically increasing function arctan was additionally used.
- 12^4: formula (1.7), the scaling function values are in the range $(0, 1]$, not $(0, 1)$,
- small inaccuracies 12_6 should be $\boldsymbol{I}_2$ instead of 1.
- 12_{16} Why is the current value (vector) and nominal value (function or configuration as in the notation below) treated differently in the notation $\boldsymbol{e}(\boldsymbol{q}(t), \boldsymbol{q}_d(\cdot), \cdot)$?
- 17^9: $[\ldots, z_n]$ should be $[\ldots, z_{n_v}]$, similarly 17_{18-17}: instead of m there should be z_{n_v}, so $59^4, 64^4$,
- The data in Fig. 2.5 would be more informative if they were presented in a different color for each task.

The remarks, questions, and comments presented above are primarily cognitive in nature and do not affect either the veracity of the dissertation's thesis (or the components of its justification) or its scientific standing.

5. Summary.

The dissertation documented the achievement of all intended goals, convincingly justifying its thesis regarding the possibility of effectively applying the VFO methodology to construct closed-loop control laws for important robotic tasks, while maintaining practical constraints. The work was written carefully (with only a few minor errors) and with attention to detail. The work is distinguished by the depth, analytical approach, and falsifiability of the presented results, which distinguishes it very positively among numerous doctoral theses. The mathematical approach utilizes the analysis of nonlinear dynamical systems, the prior estimation of vector-matrix expressions, and the intensification of Lyapunov's second principle for ingeniously selected Lyapunov functions. The proofs of Theorems (5) and Lemma (1) required mathematical proficiency in various fields (dynamical systems, mathematical analysis, matrix calculus, inequalities, estimation techniques). The work is difficult for non-specialists to understand due to its formal and multi-step (and therefore complex and lengthy) proofing method. The author attempts to simplify this task by referring to specific formulas that allow for the transformation of expressions. To emphasize the most important conclusions, the author presents his most important observations in the form of Remarks (there are 30 of them), emphasizing the validity, applicability, and possibility of extending the results, which might have escaped the reader amidst the multitude of formulas. Theoretical considerations are illustrated with simulation and experimental examples using laboratory robots.

The international co-supervision of the dissertation is worth emphasizing, which stimulates direct exchange of ideas, practical collaboration, and provides a good prognosis for the future.

In my opinion, the dissertation's usefulness for engineering sciences is unquestionable, as it concerns a practically important class of robots and motion planning tasks commonly encountered in practice. Moreover, unlike many methods in the literature, it guarantees the desired practical properties of the resulting signals (fulfillment of control constraints, estimation of task execution time, absence of chattering or oscillation in control waveforms) with reasonable computational effort, enabling implementation in embedded systems.

6. Conclusion.

After reviewing the doctoral dissertation of Rafał Sobański, M.Sc., Eng., I express the opinion that the Author has made an original and lasting contribution to the discipline of Automation, Electronics, Electrical Engineering, and Space Technologies in the field of unicycle robot motion planning, as well as their groupings for two classic robotic tasks while maintaining practically important constraints and characterized by desirable properties for the upper bound on task completion time. The scientific problems (contemporary and practically important) are formulated in the dissertation in a clear and concise manner. The Author has demonstrated a thorough mastery of scientific techniques and effectively utilizes contemporary literature on the subject. The Author's contribution to the advancement of knowledge, as documented in the doctoral dissertation, is significant, and the potential for practical applications is significant.

I therefore conclude that **the dissertation submitted for review more than meets the requirements of the Act on Academic Degrees and Titles, and I hereby request that the doctoral dissertation of Rafał Sobański, M.Sc., Eng., be admitted for public defense. Considering the arguments presented above and the quality of the publications, I formally request awarding the doctoral dissertation with distinction.**