Review of the doctoral thesis

Reviewer:

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Thesis title:

Trajectory Tracking of Differential Drive Mobile Robot by Model Predictive Control

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Thesis scope and topicality

The submitted thesis deals with modelling and control system design for a wheeled mobile differential drive robot with application of MPC in both kinematic and dynamics parts when the trajectory tracking problem is considered. The reference trajectory is not tracked directly, but by two controllers – high-level controller for generating velocity control inputs (kinematics controller) and low level controller for generating motor torque (dynamics controller). At present most works in the literature use only simple (PID) controllers on the low level or neglect the dynamical part either and assume perfect velocity tracking. In addition the MPC is often restricted only to linear case while authors use nonlinear models. Therefore the proposed approach and ideas are topical and move forward the research with the possibility to obtain better practical results. Suggested MPC-approach seems suitable for the presented task as the reference trajectory is known beforehand and it can handle both constraints and multivariable control problems, though it is more computationally demanding.

Commented thesis overview

The thesis starts by brief introduction and state-of-the art section, followed by problem formulation, objectives and assumptions. The state-of-the-art section is adequate, problem formulation is clear and objectives are chosen reasonable. I miss only one point – real-time implementation and verification – it is a pity that the thesis stays only in the theoretical and simulation level. In the assumptions I am not sure whether neglecting the time-delay between the position measurement and control action would provide good results under real-time conditions.

Next section describes suggested control strategy including planning, kinematics, dynamics and physical level. *This section is helpful, clear and easy to follow.*

Further, basics of MPC are presented for both linear and non-linear models, with the latter one transformed to linear time-varying system, together with the cost function definition and solution of the problem using the quadratic programming tools. *Standard, generally known text on MPC*.

Next part is devoted to kinematics modelling of the robot – originally nonlinear model is approximated by two suggested approaches – successive linearized model and tracking error based linear model, both leading to linear time-variant state-space models. Simulation-based comparison results of the robot following a defined trajectory show slightly better results for the latter one, error based model, when compared to the original nonlinear one.

Next chapter proposes kinematic MPC-based controller for the two LTV models and compares the results with two state-of-the art state-tracking controllers by simulation means. The results show that the error-based model with MPC converges slightly faster to the reference trajectory. *Here it is not clear how the author has chosen the two state-of-theart methods for comparison – I am not sure whether works from the beginning of the nineties can be seen as state-ofthe-art ones and If there aren't better methods for proper comparison at the moment.*

Further part is devoted to the dynamics modelling of the robot using the Newton-Euler approach, including DC motor dynamics, chassis dynamics and corresponding relations, resulting a combined linear state-space model of robot dynamics, followed by parameters identification/estimation. The resultant model is "verified" by open-loop simulation. *Here I would expect broader discussion on the parameters identification, not only the text "values are chosen so that they roughly correspond to a real robot". In addition, real-time comparison would be obviously more suitable to verify the model.*

In further section a dynamics linear MPC controller is proposed and compared with discrete PID and static feedforward control. For the MPC controller, a corresponding state estimation/observer is suggested and verified again, by simulation means. The MPC controller provides slightly better performance. *Here, again, it is not clear how the*

author chosen the competitors; moreover the tuning method of suggested discrete PIDs is not presented (just setting of K_P a K_I constants, values of K_D are not presented for some reasons at all), but it is obvious that PID performance is strongly influenced by the used tuning approach. The comparison could be more elaborated, with more relevant competitors.

Last section presents author's novel, original approach using "kino-dynamics" controller. Here, the usage of LMPC/PIDs on the low-level (dynamics) together with NMPC on the high-level (kinematics) is studied and compared thoroughly by simulation means. The presented results justify the suggested LMPC as a dynamics controller, together with the error-based NMPC for the kinematic controller, as the best choice, under given conditions. Moreover, the results highlight the importance of feedback control on the low level, considering dynamics of the robot. Here again, the same "state-of-the-art" controllers from 90's and discrete-time PIDs (of unknown tuning rules) from previous chapters are utilized for the comparison.

Conclusion and future directions sections follow, summing up main goals, methodology and achievements of the thesis together with possible future research areas. Here I would be more moderate in the comparison conclusions with respect to the competitor controllers presented. More relevant up-to-date methods and proven PIDs would be necessary. In addition, the last paragraph stating "...the thesis proposes a SIMPLE solution for the trajectory-tracking problem..." is a little bit misleading, having presented the complex shades of MPC including nonlinear problem solution and optimization. However, with the microprocessors' performance of nowadays it is a question of miliseconds, as presented in the thesis, then it seems "easy", at least when only simulating.

Finally the thesis ends by a list of references, which are adequate and relatively up-to-date, and a list of author's publications from his Ph.D. studies. He is 1st author of 7 international conference papers (1 submitted), co-author of next 6 conference papers (1 submitted, 1 accepted) and co-author of 2 journal papers of which one is in the Q3 quartile of the Scopus database. More than half of the publication relates directly to the thesis topic. The publication activity can be seen as relatively sufficient, however, student could try to submit, as a first author, also one or two internationally reviewed journals, which would help him to fine-tune priorities of his research and used methodologies.

Queries

- Why have you left the idea presented at the state doctoral exam to design and verify a real robot?

- How will the neglected time-delay influence the control process if, in reality, there is some?
- Would it be simple/difficult to incorporate also the time-delay term in the suggested design process?
- How/Why have you chosen Samson and Kanayama controllers for the "state-of-the-art" comparison?
- How have you tuned the used PID controllers?

Formal quality

Generally, the thesis is written carefully with only few formal errors concerning notation, presented equations and graphs description. Language style and grammar is relatively good with only several spelling/grammar errors and most of the work is relatively clear and easy to follow.

Final evaluation and recommendations

Although the comparison made in the thesis could be done more carefully (more relevant competitors and settings) and at least some real-time results would heighten overall impact of the work, it can be concluded the thesis fulfilled the proposed goals, being a thorough simulation analysis of the given topic. The work presents author's original results that could have a chance to be implemented further in practice, if properly tested in real-time. In his thesis, the author demonstrated the ability of independent, systematic and scientific work. Therefore

I recommend

his Ph.D. thesis for acceptance by the Committee to be presented and defended in the Information, Communication and Control Technologies study branch and, if the defence is successful, to award him the academic title "Philosophiae Doctor", abbreviated as Ph.D.

Zlín, May 10th, 2017

Doc. Ing. František Gazdoš, Ph.D.