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Review of Dissertation Thesis

Title: Algorithms for Complex Bipedal Walking
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Reviewer: doc. Ing. Ondřej Straka, Ph.D., University of West Bohemia

Dissertation thesis written by Ing. Kamil Dolinský deals with design of algorithms for parametric system identification and algorithms for state estimation with a special focus on a walking robot model.

The system identification task is searching for a mathematical system model, in this case model parameters, based on measured input-output data. In the thesis, the off-line approach to identification has been chosen consisting of first collecting the measured data and subsequent estimation of the model parameters.

The model with identified parameters was then used in the state estimation task, which strives for finding values of indirectly measured variables called state. In the case of the walking robot, the interest focused on absolute orientation angle, which was estimated. Knowledge of the state makes it possible to close the control loop to enable walking of the robot.

The thesis written in English within ca. 100 pages is split into five chapters. After the short introductory chapter, the second chapter focuses on a description of the walking robot model including the swing and impact phases of its motion and introduction of three state estimation algorithms, which are further modified for the considered robot model. Next, the design of the method for parametric identification of the robot model is presented in the third chapter. The fourth chapter contains the modified state estimation algorithms for the robot model, in particular the algorithms of the extended Kalman filter (EKF) and the unscented Kalman filter (UKF). The thesis is concluded by the fifth chapter followed by the appendices.

The goals of the thesis, described in the introductory chapter, are three: i) to solve the problem of model parameter estimation of an underactuated robot without direct absolute orientation angle measurement, ii) to find how to utilize linear structure of the model with respect to the parameters if the absolute orientation angle measurement is noisy, and iii) how to estimate the absolute orientation angle using measurements obtained by sensors typically placed on the robot.

The solution to the first goal introduced in chapter 3 is based on utilizing sensors that are placed on the robot to obtain an indirect absolute orientation angle measurement. This allows elimination of the absolute orientation angle from the model and replacing it by a transformation of the indirect measurements. The thesis proposes using either distance measurements or an inertial measurement unit (IMU) measuring acceleration and angular velocity. The noisy measurements are then used in a design matrix that relates the measured torques and the sought model parameters. To solve the second goal a method based on the maximum likelihood principle has been proposed in Section 3.3. Once the model parameters are found, the third goal of the thesis can be treated, which is estimation of the absolute orientation angle utilizing the identified model. For this purpose, the extended Kalman filter and the unscented Kalman filter have been modified to respect the impact phase of the robot motion.

It can be said that solving the above goals is highly desired. A quality system model together with availability of the estimate of directly unmeasurable variables are prerequisites for future treatment of the robot, in particular its successful control. From the performance analyses of individually designed methods based on either simulation examples or a physical experiment, it follows that the proposed identification and state estimation methods achieve better performance in comparison with the state-of-the-art identification an estimation methods.

The text of the thesis has not avoided some inaccuracies, e.g.:

- While Chapter 2 considers a non-additive model (2.34) – (2.37), the unscented Kalman filter introduced in Section 2.5.2 is in the form for models with additive noises.
- In Section 2.5.2 describing the unscented Kalman filter, the square-root of a matrix $\sqrt{A}$ and notation $(A)_i$ are undefined.
- Section 2.5.3 describing the hybrid extended Kalman filter first treats the model (2.19), which is a deterministic dynamics equation and shortly in equation (2.67) noisy dynamics appears without any justification and similarly, the stochastic measurement equation (2.68) is provided without any justification.
- The symbol Σ_Q in (2.69) is undefined.
- The term hybrid is used in the thesis in two associations. The first one means continuous-discrete when dealing with the extended Kalman filter, while the second one means switching the swing and impact phase of the robot motion.
- The relation (3.74) is probably incorrect as the right hand side contains only Jacobian and Hessian.
- In the proposed EKF algorithm on page 59, the order of steps in 2.a) should be reversed – first apply the control $u(t_k)$ and then read the measurement $y(t_k)$. The reason is that the model (2.30) considers the output $y(t_k)$ to be directly dependent on the input $u(t_k)$.
- Despite the fact that the relation (4.16) is based on a heuristics, its justification could be provided.
- The meaning of the variable indexed by symbols a and b in (4.21) and (4.22) of the proposed unscented Kalman filter is not explained. This also holds in (4.32) for variables indexed by $(i+)$ and $(i-)$.

A list of typos found in the text follows:

- 5th below (2.23): The symbol q_e^+should be replaced by $\dot{q}_e^+$.
- The constants $\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3, \mathbf{k}_4$ are bold in (2.32) and non-bold in (2.33).
- When evaluating Jacobi matrices in (2.40) and (2.43), the value of the input u should be specified.
- In relation (2.53) the variable x should not have hat.
- In the relations for the Jacobi matrices L, H, and M on page 24, the variables miss bars.
- In relations (3.59) – (3.61) the term $e(t_k)$ should be replaced by $e_{\tau,\eta}(t_k)$.
- In relation (3.70), the variable β misses hat.
- In relations (4.8), the noise w should be replaced by the noise v.

The text written in English contains only minor language problems, e.g.:

- pp. 7: ... the state estimators helps recover ...
- pp. 10: „During 3D walking robots which would walk freely without the need for support in the lateral direction"
- pp. 45: „... a Monte Carlo simulations ..."

Despite the above rather minor issues, the thesis is well and clearly written. The techniques addressing the goals were selected suitably and lead to improved performance of the proposed system identification and state estimation methods for the considered model in comparison with other state-of-the art methods. The contribution of the thesis can be seen in the new methods for system identification and state estimation for the considered model of the walking robot, which together lead to quality estimates of the absolute orientation angle of the robot. The methods were designed in such a manner that their application to another model would be straightforward. Availability of the above mentioned methods is indispensable for control design of the walking robot and subsequently for future walking robot applications. The achieved results were published in a prestigious impacted journal and eight conference papers presented at quality international conferences, which means that the published results have already been reviewed by field experts. This implies that the thesis meets the requirements of independent creative scientific work. In conclusion, **I recommend the work for the defense.**

Plzeň
October 25, 2017

doc. Ing. Ondřej Straka, Ph.D.

General questions for the defense:

1. The method for model parameter estimation in Section 3.3 closely reminds the Expectation-Maximization (EM) algorithm. Could the proposed method be considered as a special variant of the EM algorithm?
2. In Section 3.4.1 it is written that the simulation analysis was carried out even for the variance of the absolute orientation angle noise equal to 10^{-3}, in which case the optimization had not been finished and the estimates were considered to be unreliable. Does this imply a limitation for real applications of the methods?
3. In relation to parameter estimation by the hybrid (continuous-discrete) extended Kalman filter described in Section 3.4.1, how was the parameter dynamics modelled?
4. According to Table 4.3, why the estimate quality expressed using sum of squares achieved by the EKF degrades with adding new sensors? The estimates achieved by the UKF accord with the assumption that adding new sensors improves (or at least cannot degrade) estimate quality.