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ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE

PHD THESIS EVALUATION REPORT

Thesis title: **Algorithms for Complex Bipedal Walking**

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The thesis focuses on parameter identification and state estimation of under-actuated bipedal walking robots. In particular, critical aspects of robot walking are analysed in two dimensional (2D) space, which is a preliminary step towards 3D walking, needed for real applications. From theoretical point of view, the problem to solve is of high complexity even for the given 2D case. This is caused not only by nonlinearity of the problem and considered under-actuation, but also by fundamental difficulties in estimation of robot orientation with respect to the ground. The thesis is written in very good English on 100 pages (including an appendix and list of author's publications). It consists of six chapters, which are outlined below.

Chapter 1 - Introduction and thesis objectives

The introduction starts with general motivation of the problem to solve. It is stated that a substantial improvement in robot walking has been achieved thanks to controllers designed based on modelled dynamics of the robot, compared to earlier approaches based on heuristics or analysis of static forces. This naturally brings the need for algorithms for building a model and identifying parameters describing the mass and inertia distribution, friction and actuation impacts on the overall motion of the robot. Due to the considered under-actuation, the robot walking is achieved by keeping the robot in a stable limit cycle. For this task, an estimation of the absolute orientation of the robot with respect to the ground is needed. This can be safely done if and only if the foot of the robot is flat on the ground. This, however, is only for a very short period of time during the walking cycle. Besides, the walking robots are often considered with point-feet, which makes this problem even more difficult. Thus, a proper instrumentation and signal processing is a critical task to be solved.

The motivation section is followed by brief state of the art on identification and parameter estimation in the given problem. More or less, this section just states that the problem has been solved since 80s of the last century and is actual till today. It only provides an overview what has been done by several other authors active in the subject. The state of the art section is not critical at all. It does not analyse the depth of the research done so far and does not explicitly identify problems which are still open. The thesis objectives should naturally arise from such a critical evaluation of state of the art. Unfortunately, it is not the case here. Nevertheless, three problems to solve (objectives) are stated as follows:

I. How to estimate the parameters of an under-actuated walking robot model when direct measurement of Absolute orientation (AO) is not available.

II. How to exploit the linear structure of the walking robot model with respect to the parameters when the measurements related to the AO are noisy.

III. How to online estimate the AO angle from sensors typically available for the walking robots.

Despite the missing justification of the objectives in the state of the art section, their originality is documented by the author's publications on these topics, which had to undergo a proper review. In the rest of the Chapter I, outline of the thesis is provided.

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Chapter 2 – Preliminaries

The model of planar bipedal walking robot and the fundamental aspects of walking modelling are highlighted. The robotic walking is characterised as a periodic switching between swing phase and impact phase. The model is then derived using Euler-Lagrange approach, resulting in a set of nonlinear differential equations. This is further turned to the state space model, where the state vector is composed of configuration angles and their angular velocities. A considerable attention is also paid to the impact phase which is turned to re-initialization of the model with new initial conditions determined as reaction to the impulsive forces. Subsequently, the model is turned to a discrete form using either Euler or fourth order Runge-Kutta method. The rest of this section outlines estimation algorithms which are to be applied on the robot walking. In particular, Extended Kalman Filter (EKF), Unscented Kalman Filter (UKF) and hybrid extended Kalman filter (which estimates not only the states, but also the model parameters) are considered. This section is very well structured, all the aspects are methodically well described.

Chapter 3 – Offline identification for bipedal walking robots

This chapter provides the key results of the thesis in the sense of parameter estimation based on inertial or distance measurements. For the purpose of parameter estimation, first, a new parameter set β is introduced so that the model is linear with respect to this new set, as given in equation (3.1). Note that in order to identify the parameters β from the set of linear equations, all the state variables need to be obtained, either from measurements (relative angles) or by approximation (first and second derivatives obtained by central differences formulas). The critical problem is however determination of the absolute orientation angle. Two methods are proposed in the thesis for this task. The first method uses distance measurements by a sensor mounted on the leg of the robot pointing to the ground. The second method, which has higher potential towards practical implementation, is then based on measurements from inertial measurement unit (IMU) composed of two accelerometers and one gyroscope. Next to forming the nonlinear equation to transform the measurements into the matrix entries, the key task being solved is handling the measurement errors. This task is relatively easy for the first method resulting to equation (3.17). As demonstrated, transforming the measurements from IMU is considerably more complex task. Applying a careful transformation using rotation matrices, and considering statistical characteristics of the measurement errors, the model representing whole dataset based on measurements is given in equation (3.45). Finally, a procedure for estimating the parameter set β is then proposed based on linear least-square regression. In a subsequent par to the chapter, the measurement noise it taken into account in estimating the most likely values of physical variables. As the main result, maximum likelihood estimation (MLE) method is proposed to estimate parameters from open loop noisy data, which leads to minimization of sum of squares (3.61). A complete procedure for iterative solution of given nonconvex optimization problem follows.

The proposed methodology for parameter identification is then applied to a simple structure robot consisting of three links and a laser distance sensor for measuring the distance from the ground. Although the application example is considerably simpler than the robot structure with five links considered in the problem formulation, it serves well for the demonstration purpose. After the model composition in the transformed parameter set β, Monte Carlo simulations are utilized to analyse the performance of the

proposed MLE method, which is cross-compared with several alternative approaches. As it results from the comparison, the MLE algorithm provides far the best performance.

The chapter is then concluded by an experimental study of parameter estimation for a leg of a laboratory walking robot. The given problem is substantially simplified, as only two angles are considered. From the comparison between the measured data and simulated results by identified model, the proposed MLE method is again superior to the alternative approaches. Next to the results of statistical analysis, the performance is also documented visually in two figures. Inclusion of the experimental section in rather theoretical work is very beneficial. However, both the set-up under consideration and the achieved results are not very well described. It would be very useful to see a scheme with orientation of the angles, next to the photograph. The question is why the identified parameters are not compared with the physical parameters. Figures 3.4 and 3.5 are difficult to read. Their description should be much more detailed.

Chapter 4 – Online state estimation

The chapter deals with applying the model based techniques to estimate the absolute angle from the available measurements. First, critical aspects of successful estimation are discussed. It mainly includes detection of the impact and successive swapping of the legs' roles. Then as the main results the Extended Kalman Filter and Unscented Kalman Filter, which were described in Chapter 2, are adapted for the given task. The algorithms are then applied to estimate absolute angle of a three-link bipedal walking robot being controlled by a nonlinear control algorithm taken from literature. The two relative angles are supposed to be measured using optical incremental sensors, whereas IMU mounted on the torso provides measurements of absolute angular velocity and acceleration in the coordinates of the IMU. Both the measurement and dynamical models for the observer are formed. The associated EKF and UKF estimators are then reinitialized when an impact event is detected. This is done by remapping the states and the system matrices by the impact map outlined in Chapter 2. Independently, a model in the configuration angles is derived and used for the controller design, which is outlined considering the major steps. In Monte Carlo simulation experiments, both EKF and UKF are applied taking into consideration various available measurements. From the statistical analysis of the simulations, it results that the UKF filter performs considerably better than EKF. Besides, it is clearly shown that if the model does not fit the true behaviour of the robot perfectly, the additional measurements are crucial for estimating the absolute orientation angle. The section is concluded by graphs with simulations, showing perfect match between the estimated and true values. Similarly to the previous chapter, on the one hand, the presented results are theoretically advanced with clear contribution to the subject. On the other hand, the validation given here by a simulation experiment could have been presented better. It would be interesting to see more plots with results, for example for the cases where the system-model match is not perfect. The question also is why the experimental validation is not included, taking into account that a robot prototype is available, as presented in Chapter 3.

Chapters 5-6 – Conclusions and Appendix

The thesis is concluded by highlights of the three solved problems followed by the summary of author's contributions. Then, several open problems are briefly discussed. In the appendix, parameters and

matrices of models considered in the thesis are provided. Mainly it is the 5-link robot model, described in Chapter 2.

Summary and recommendation

The thesis provides a clear contribution to the subject of bipedal robotic walking. The problem under consideration is very complex not only due to its highly nonlinear nature, but also due to discontinuities in the walking pattern, at which the model has to be reinitialised. On the one hand, results provided in the thesis are strong from the theoretical point of view. On the other hand, sections presenting simulation and experimental validation could have been more extensive and better documented. Besides, there are several robot configurations across the thesis, which is rather impractical and makes the problems difficult to follow. For example the 5-link model is described in detail, but in the simulation examples, only 3-link robot is used.

Concerning the stated problems to solve (thesis objectives), all of them have been fulfilled. The problems I. and II. were solved in Chapter 3. The main result is the formulation of the parameter identification as a linear regression problem, where the missing information in the design matrix (due to missing information on the absolute orientation angle) was supplemented based on indirect measurements. Besides, the problem of noisy measurement data was solved by Maximum likelihood parameter estimation, where the errors are recursively minimised. The problem III was solved in Chapter 4 where the well-known Extended Kalman Filter and Unscented Kalman Filter were successfully designed to handle the problem of absolute orientation angle estimation during controlled walking of the robot. The quality of research results presented in the thesis is also supported by publications of the author. In particular, it is by a paper presented in IEEE Transactions on Control System Technology – one of the best journals in the field of applied control theory, and three conference papers indexed in Web of Science. To conclude, due to high quality of presented research results and clear contribution to the subject of bipedal robotic walking, I fully recommend the thesis for defence.

Question for the defence

1. Could you provide a broader state of the art context in the subject of robot walking? Are the model based approaches truly superior with respect to heuristic methods and methods based on artificial intelligence, e.g. machine learning?
2. During the stable walking, variations of absolute orientation and relative angles should be relatively small, particularly for the 5-link robot. The structure of the models could be simplified if the conventional approximation of goniometric functions of small angles was applied ($\cos\alpha \cong 1, \sin\alpha \cong \alpha$). Why this simplification was not used? Would it cause fundamental constraints to robot functioning?
3. The critical point for a successful estimation of absolute orientation angle during walking is a proper setting of the initial conditions when the impact occurs. The remapping is however made under several simplifying assumptions (the reaction forces are impulsive, there is no instant change in the angles, but only in velocities, etc.). The conditions might be considerably different in reality, especially when walking in terrain (it does not need to be ideally flat, can be soft or even

muddy, slippery, etc). Has this problem been solved in literature? Would be the proposed approach applicable to these cases?

4. Most of the parameters of the models are physical (link lengths, masses, inertia). The identification problem would be much simpler, if these known parameters were used in the model and only those which cannot be directly measured (mainly friction and actuation impacts) would be identified. Has this option been taken into account?
5. In the simulation example section 3.4, parameters of the model are given by (3.80). Why the corresponding parameters obtained from the identification procedure are not given? Are they close to the model parameters, when transformed to the linear set (3.81)? The same question applies also for the experiment section 3.5. At least the link lengths and masses should be known precisely.
6. Were another experiments performed within the work? It is a bit disappointing that the identification algorithms were applied to a single leg set-up only. What is the current full configuration of the available robot prototype?
7. In real applications, most likely, redundant sensors would be used. Can you provide any comments on ideal instrumentation for robot walking?

In Prague, December 21st 2017

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