Lateral guidance of independently rotating wheel pairs using feedback linearization

Introduction (300 words)

A main aspiration of the DLR project Next Generation train (NGT) is to include mechatronic systems in railway vehicles, because this opens a broad field to improve the running dynamics.
Mechatronic systems enable the use of independently rotating wheels (IRW), which afford an active guidance control to stabilize the lateral movement. Due to the different wheel speeds low creepage is possible in every lateral position of the wheel pair. In that way e.g. wear and thus maintenance costs can be reduced significantly while energy efficiency is improved.
For this reason the NGT coaches are equipped with IRW and each wheel is driven by a separate motor. Hence, the motors can be used for both traction and steering and no additional actuators are required. However, the control design is challenging due to the complex non-linear system, mainly caused by the non-linear wheel-rail profile. Beyond that the guidance has to be robust to cover various scenarios regarding e.g. different velocities, track irregularities, curving and wear profiles.
In previous works the possible wear reduction of the IRW was proven [1] a robust control for a 1:5 scaled roller rig was established [2] and transferred to full scale multibody models [3].
In this survey, a control design via feed-back linearization is presented, offering the possibility to explicitly address non-linearities in design. In this way, elaborate gain scheduling between linear designs in various operating points can be avoided. At first, an overview on feedback linearization is given and the employed analytical model is introduced. After some comments on the simulation environment containing models in Modelica and Simpack and how to connect them via Functional Mock-up Interface (FMI), the resulting control structure is shown. In the end, the controller gains are specified by numerical optimization and simulation results for multibody models are discussed.

Methods (300 words)

The concept of feedback linearization as stated in [4] enables a controller design for non-linear plant models with state $\boldsymbol{x}$ in the form

$$\dot{\boldsymbol{x}} = f(\boldsymbol{x}) + g(\boldsymbol{x})u\,;\; y = h(\boldsymbol{x}).$$

Characteristic system values are the dimension m of $\boldsymbol{x}$ and the relative degree r, which determines the number of derivations of y until $y^{(r)}$ explicitly depends on u. Regarding to [4] the system is transformed by a non-linear virtual input $v(\boldsymbol{x})$ into one with closed loop system characteristics of multiple integrators. Hence, a stable trajectory following can be accomplished by a linear control law and the feedback of $y, \dot{y}, \dots, y^{(r-1)}$. In the case of $m < r$ zero dynamics can occur and if they are unstable the concept fails. Nevertheless, the zero dynamics and r can be changed by another choice of u or y.

To enable control design an analytical model of a single wheel pair with four degrees of freedom, namely the lateral position y_w, the yaw angle of the axle beam Ψ and the velocities of left and right wheel $\omega_{ri/le}$ is established in [5]. The main assumptions are conical wheels, constant longitudinal velocity and contact forces according to Kalker's linear theory [6].
In relation to [7] the language Modelica offers the possibility to derive feedback linearization conveniently by automatically inverting models. In that way, the inverse analytical model is used as core part of the controller and the controller gains are adjusted in terms of stability and performance using single wheel pair multibody models from the DLR Railway Dynamics Library [8].
The standardized FMI empowers the transfer of the controller from Modelica to full scale multibody models of the NGT in Simpack running on realistic track scenarios. In addition, the Simpack simulation is coupled with the DLR in-house optimization tool MOPS [9] based on Matlab and the control parameters are optimized to increase performance.

Results (300 words)

To analyze the system in terms of feedback linearization the equations of motion may be summarized as

$$\begin{pmatrix} \ddot{y}_w \\ \ddot{\Psi} \\ \dot{\omega}_{ri} \\ \dot{\omega}_{le} \end{pmatrix} = \begin{pmatrix} f_1(y_w, \dot{y}_w, \Psi, \dot{\Psi}) \\ f_2(y_w, \dot{y}_w, \Psi, \dot{\Psi}, \Delta\omega) \\ f_3(y_w, \dot{y}_w, \Psi, \dot{\Psi}, \omega_{ri}) - g\,\Delta\tau \\ f_4(y_w, \dot{y}_w, \Psi, \dot{\Psi}, \omega_{le}) + g\,\Delta\tau \end{pmatrix}.$$

Hereby the steering torque $u = \Delta\tau$ is allocated in reversed directions to the left and right wheel. Choosing $y = y_w$ leads to a state space representation with $r = 5$ and $m = 6$. Consequently, the feedback requires the knowledge of $y_w{}^{(1),\dots,(4)}$, which is not suitable to measure.
Nevertheless, it is evident that lateral steering depends on Ψ and due to the different wheel speeds $\Delta\omega = \omega_{ri} - \omega_{le}$, $\Delta\tau$ affects Ψ mainly by $\Delta\omega$. This implies a cascaded control structure (see Fig. 1) under the assumption of different time scales. Thus, besides the full state $\boldsymbol{x}$ only $\dot{y}_w$ as highest derivative of the output is required. It is assumed that $\Psi, \dot{\Psi}$ and $\omega_{ri/le}$ are directly available from measurements whereas y_w and $\dot{y}_w$ are estimated by an observer. Furthermore, the cascaded control is advantageous, because $\Delta\omega$ is taken into account as feedback and the order of the inverse models is decreased, which reduces the complexity of the inversion.

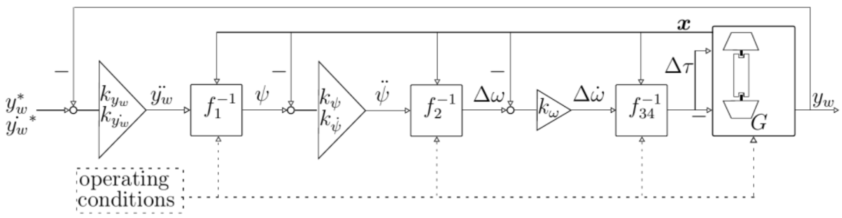

Fig. 1 Cascaded control structure for IRW

The control structure is implemented in Modelica to adjust the controller gains for each loop separately according to [10]. Stability of the whole system can then be proven by the linear-analysis toolbox. The controller parameters for the 1:1 system (see Fig 2) running with 300 km/h on a straight laterally disturbed track are optimized regarding actuator effort and lateral position, which is related to a wear decrease. The running dynamics are compared with a similar high speed train on conventional wheelsets. The lateral position of both vehicles is shown in Fig. 3. The preliminary results depict sufficient lateral dynamics of the NGT and it becomes clear that a wear reduction of more than 60 % can be attained.

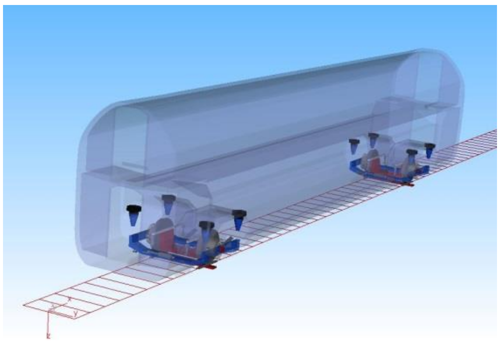

Fig. 2 Simpack MBS of NGT

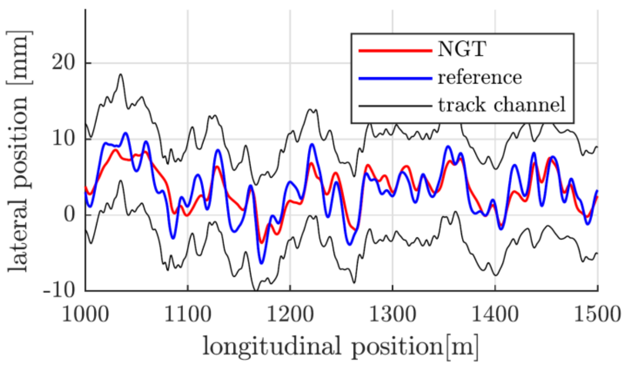

Fig. 3 Lateral position of reference vehicle and NGT on disturbed track

Conclusions and Contributions (300 words)

In this work the methodology of feedback linearization is applied successfully to the lateral control of IRW. Due to the feature of Modelica to automatically invert models, this approach can effectively be adopted to different vehicle models. Furthermore, variable operating conditions can be fed to these models as inputs. In this way, controllers for the whole operating range of the vehicle can be attained without gain scheduling or robust control techniques.

The established cascaded control structure is based on a feedback of the differential wheel speed $\Delta\omega$. Thus, the advantageous property of the IRW, namely the possibility of low creepage in every lateral position, is directly taken into account. Preliminary results of multibody simulations verify that the established controller significantly improves the wear characteristics compared to a reference vehicle and hence the goal of reduced maintenance costs is met. In addition a considerable benefit concerning the running dynamics like curving and passenger comfort is expected, due to the sufficient lateral position of the wheel pair, but not yet analyzed. Beyond that, the usage of advanced inverse models in the control layout facilitates further refinement. In this way more non-linearities, especially non-linear wheel profiles can be considered, which enhances a more robust control. Furthermore, the controller is to be tested on the 1:5 scaled roller rig, to examine the robustness due to profile changes.

[1] B. Kurzeck, A. Heckmann, C. Wesseler und M. Rapp, „Mechatronic track guidance on disturbed track: the trade-off between actuator performance and wheel wear,“ *Vehicle System Dynamics,* Bd. 52, pp. 109-124, 2014.

[2] A. Heckmann, C. Schwarz, T. Bünte, A. Keck und J. Brembeck, „Control Development for the Scaled Experimental Railway Running Gear of DLR,“ in *24th Symposium of the International Association for Vehicle System Dynamics (IAVSD 2015)*, 2016.

[3] A. Heckmann, D. Lüdicke, G. Grether und A. Keck, „From Scaled Experiments of Mechatronic Guidance to Multibody Simulations of DLR}s Next Generation Train Set,“ in *25th International Symposium on Dynamics of Vehicles on Roads and Tracks*, 2017.

[4] A. Isidori, Nonlinear control systems. an introduction., 2nd ed. Hrsg., Berlin. :: Springer-Verlag. :, 19890000.

[5] G. Grether, „Dynamics of a running gear with IRWs on curved tracks for a robust control development,“ *PAMM,* 2017. accepted for publication.

[6] J. J. Kalker, Three-Dimensional Elastic Bodies in Rolling Contact, Dordrecht (nl) :: Kluwer :, 1990.

[7] M. Thümmel, G. Looye, M. Kurze, M. Otter und J. Bals, „Nonlinear Inverse Models for Control,“ in *4th International Modelica Conference*, 2005.

[8] A. Heckmann und G. Grether, „The DLR RailwayDynamics Library: the Crosswind Stability Problem,“ in *Proceedings of the 12th International Modelica Conference*, 2017.

[9] H. D. Joos, „A multiobjective optimisation-based software environment for control systems design,“ in *Proceedings. IEEE International Symposium on Computer Aided Control System Design*, 2002.

[10] J. Reiner, G. J. Balas und W. L. Garrard, „Flight control design using robust dynamic inversion and time-scale separation,“ *Automatica,* Bd. 32, pp. 1493-1504, 1996.

[11] D. Enns, D. Bugajski, R. Hendrick und G. Stein, „Dynamic inversion: an evolving methodology for flight control design,“ *International Journal of Control,* Bd. 59, pp. 71-91, 1994.