Novel Developing Environment for Automated and Electrified Vehicles using Remote and Distributed X-in-the-Loop Technique

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***Abstract*—This Paper contributes to an approach for integrated development, optimization and scientific investigation of coupled systems. The focus here is on real-time networking of test fields with model-based development environments.**

***Index Terms*—X-in-the-Loop, brake, system, automated, electric, vehicles, observer, distributor, hard coupling, soft coupling, remote, distributed**

I. Introduction

The paradigm change to a fully automated vehicle is a big challenge for the development of modern vehicles. In this regard, the complexity of designing tasks for the developers of highly automated systems increases, especially in the case of electric vehicles. Electric vehicles bring new actuators and more complex architecture that should be properly considered on various design stages. Hence, it is important to investigate new methodologies for robust and reliable developing of complex systems in automotive context. One of efficient trends in this area can be application of X-in-the-Loop technologies for development design, validation and testing.

In general, X-in-the-Loop enables an integrated developing approach across different domains of automated and electrified systems. Some examples of X-in-the-loop technologies in automotive development can be found for fuel cell vehicles performance optimization [1], automotive powertrain design [2], [3], advanced driver assistance systems [4], [5], virtual homologation of automated driving functions [6]. In these studies, the focus was on the application of X-in-the-Loop technologies for a particular, stand-alone design task. As a result, a reasonable advancement of this approach can be in establishing flexible and versatile validation and testing environment, which can be used for running several design tasks simultaneously. A relevant architecture of such an environment has been discussed in previous work of the authors [7]. The presented paper will introduce several elements of this architecture in more detail.

II. X-in-the-Loop technique

X-in-the-Loop can be derived from the classic hardware-in-the-loop approach. This approach relates to the testing of electronic control units by simulating a virtual vehicle in real-time, also known as residual bus simulation.

Nowadays, X-in-the-Loop is established in industry and science. However, there is still no common understanding of the methodologies. Due to the strong relation on the technical aspects in the development of mechatronic systems, the term X-in-the-Loop is limited in many studies to the conventional definition of rapid control prototyping (RCP), model- (MIL), software-/processor- (SIL/PIL) and hardware-in-the-loop (HIL). Humans, peripheral processes and other phenomena are not always taken into account. Therefore, the X-in-the-Loop method should be clarified and generalized for all technical processes for automated driving across all automation level.

In accordance with the most recent scientific status, the definition of X-in-the-loop can be updated in accordance with Fig. 1. The system design is categorized into the domains "human", "process" and "function", which are interacting with each other via specific interfaces. The system process interacts via Human-Machine-Interface (HMI) with the human and via sensors/actuators with the functionality. The testing environments are distinguished into a virtual and physical domain. The cross-connection between virtual and physical domains is defined as hybrid testing. Coupling these domains results into a specific X-in-the-Loop technique. In particular novel techniques such as Test-Rig-in-the-Loop (TRIL) [8], Human-Model-in-the-Loop (HMIL), Robot-in-the-Loop (RIL), Driver-in-the-Loop (DIL) can be mapped. Next section gives a practi-

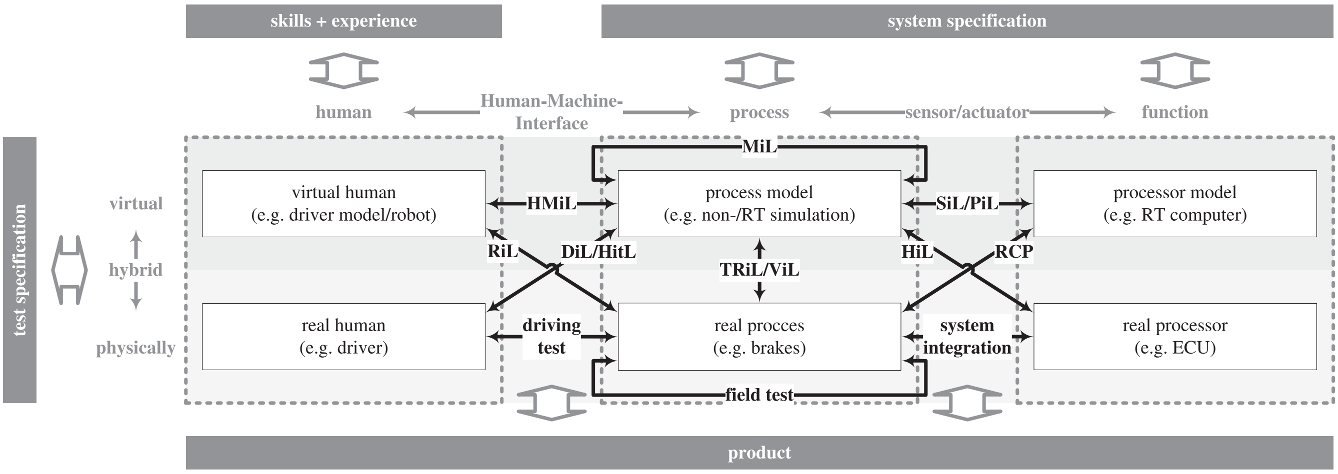

Fig. 1. Clarification of the X-in-the-Loop approach

cal example, how the proposed methodology and architecture can be realized for practical tasks related to the brake system design of an automated electric vehicle.

III. Multi-domain testing of brake system related to automated vehicles using X-in-the-Loop environments

A. Overview

Fig. 2 introduces the implementation of a hard and soft coupling on the brake system. The reference system is a full vehicle simulation that runs on a real-time system. The outputs of the reference system are the angular speeds of the wheels $\omega^{*[FL..RR]}$, the pressure of the master brake cylinder $p^{*[MC]}$, the target brake pressure for the wheel brakes $p^{*[FL..RR]}$ and the vehicle velocity $v^{*[GC]}$. This signals are sent via a UDP/VPN communication protocol to the HIL system. The measured wheel brake pressure $p^{[FL..RR]}$ at the HIL and the targeted wheel speeds $\omega^{*[FL..RR]}$ are used for determining the reference values p^* and ω^* for the brake dynamometer. In addition, filtering and prediction methods are required here. The response of the wheel brake is observed by an observer, which corrects a reduced order model of the physical brakes. In the last step, the correction and the observed system outputs from the HIL and brake dynamometer are used to distribute the braking torque $M^{[FL..RR]}$ back for each wheel. According to the usage of this technique, the closed-loop feedback is defined as soft coupling. A feedback loop without using the prediction and distribution technique is realized then as a hard coupling.

B. Filtering

Noise is usually not desirable in a technical process. By coupled closed-loop systems noise can lead to instability that negatively influences the result or even leads to destruction of test equipment. In such cases, the raw signal must be filtered. However, analogue filters in particular can influence the phase of the signal, so that the observation of the system behaviour can be negative affected. Alternatively, digital filters are mainly used, which are basically divided into recursive filters with an infinite impulse response (IIR filter) and non-recursive filters with a finite impulse response (FIR filter). They have enhanced properties such as (i) specific filter curves, (ii) real-time capability and (iii) linear phases. Eq. 1 and 2 show a generic representation of such filter, where z is a transformation of sampling a linear time-invariant (LTI) system in accordance with $z = e^{\tau_s s}$.

$$H_{IIR}(z) = \sum_{n=0}^{\infty} h_n z^{-n} = \frac{b_0 + b_1 z^{-1} + \cdots + b_n z^{-n}}{a_0 + a_1 z^{-1} + \cdots + a_n z^{-n}} \quad (1)$$

$$H_{FIR}(z) = \sum_{n=0}^{N} h_n z^{-n} = \frac{b_N + b_{N-1} z + \cdots + b_0 z^N}{z^N} \quad (2)$$

C. Prediction

The coupling of test systems is based on the exchange of information via communication media. However, the use of communication media induces a time delay. The communication time must be small enough not to influence the native system behaviour. Nevertheless, if there is an influence introduced by time delay, the prediction algorithms can compensate the communication time delay. If the inherent system behaviour is known, the system behaviour can be predicted using a model-based approach. Since the system behaviour is generally not known, the Smith predictor for predicting the signal behaviour is proposed as a generic approach in the presented study.

$$y_{t-\tau_d}(s) = e^{-\tau_d s} y_t(s) \quad (3)$$

$$y_t(s) = e^{\tau_d s} y_{t-\tau_d}(s) \quad (4)$$

To transfer the method to LTI systems the term $e^{\tau_d s}$ in Eq. 4 must be linearised. Therfore the approach according to Eq. 5 and Eq. 6 is used, where N is representing the order of the predictor. This means that the system derivatives must be known or must be determined.

$$e^{\tau_d s} = \sum_{n=0}^{\infty} \frac{(\tau_d s)^n}{n!} \quad (5)$$

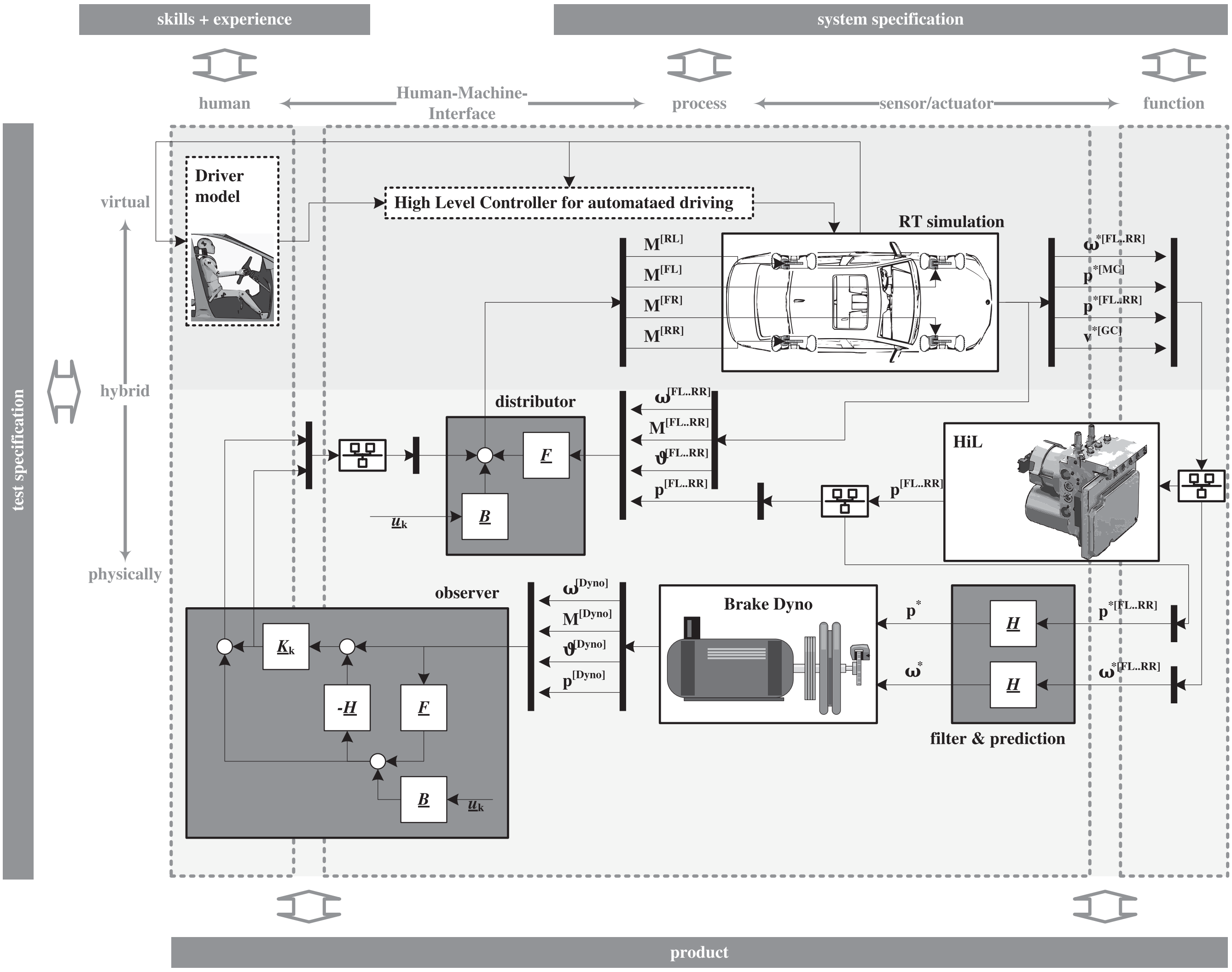

Fig. 2. X-in-the-Loop example for testing brake systems of automated vehicles

$$\mathcal{L}^{-1}\{y_t(\boldsymbol{s})\} \approx \sum_{n=0}^{N} \frac{(\tau_d)^n}{n!} \overset{(n)}{y}_{t-\tau_d} \tag{6}$$

D. Observer

An observation is a concept that estimates the actual system state using measured signals and a reduced order model. Disturbance like derived by noise and other influences are compensated by the observer and the model error is corrected. Besides the Luenberger observer, the Kalman filter is one of the common implementations of an observer concept for real-time systems. His mathematical formulation is based on a stochastic estimation of the variance from a linear time-invariant system. The formulation applied in this study is as follows:

$$\underline{\boldsymbol{x}}_{k+1} = \underline{\boldsymbol{A}}_k \underline{\boldsymbol{x}}_k + \underline{\boldsymbol{B}}_k \underline{\boldsymbol{u}}_k + \underline{\boldsymbol{\upsilon}}_k \tag{7a}$$

$$\underline{\boldsymbol{y}}_{k+1} = \underline{\boldsymbol{C}}_k \underline{\boldsymbol{x}}_k + \underline{\boldsymbol{\nu}}_k \tag{7b}$$

Initialisation:

$$\underline{\boldsymbol{P}}_0 = cov\,\{\underline{\boldsymbol{x}}, \underline{\boldsymbol{x}}\} = \underline{\boldsymbol{\sigma}}_x^2 \tag{8a}$$

$$\underline{\boldsymbol{R}}_0 = cov\,\{\underline{\boldsymbol{y}}, \underline{\boldsymbol{y}}\} = \underline{\boldsymbol{\sigma}}_y^2 \tag{8b}$$

$$\underline{\boldsymbol{Q}}_0 = cov\,\{\underline{\boldsymbol{z}}, \underline{\boldsymbol{z}}\} = \underline{\boldsymbol{\sigma}}_z^2 \tag{8c}$$

Prediction: (*a priori*)

$$\underline{\boldsymbol{P}}_{k+1|k} = \underline{\boldsymbol{F}}_k \underline{\boldsymbol{P}}_{k|k} \underline{\boldsymbol{F}}_k^T + \underline{\boldsymbol{Q}}_k \tag{9a}$$

$$\underline{\boldsymbol{x}}_{k+1|k} = \underline{\boldsymbol{F}}_k \underline{\boldsymbol{x}}_k + \underline{\boldsymbol{B}}_k \underline{\boldsymbol{u}}_k \tag{9b}$$

Innovation:

$$\underline{\boldsymbol{z}}_{k+1} = \underline{\boldsymbol{y}}_{k+1} - \underline{\boldsymbol{H}}_{k+1|k} \underline{\boldsymbol{x}}_k \tag{10a}$$

$$\underline{\boldsymbol{S}}_{k+1} = \underline{\boldsymbol{H}}_{k+1} \underline{\boldsymbol{P}}_{k+1|k} \underline{\boldsymbol{H}}_{k+1}^T + \underline{\boldsymbol{R}}_{k+1} \tag{10b}$$

Correction: (*a posteriori*)

$$\underline{\boldsymbol{G}}_{k+1} = \underline{\boldsymbol{P}}_{k+1|k} \underline{\boldsymbol{H}}_{k+1}^T \underline{\boldsymbol{S}}_{k+1}^{-1} \tag{11a}$$

$$\underline{\boldsymbol{x}}_{k+1|k+1} = \underline{\boldsymbol{x}}_{k+1|k} + \underline{\boldsymbol{G}}_{k+1} \underline{\boldsymbol{z}}_{k+1} \tag{11b}$$

$$\underline{\boldsymbol{P}}_{k+1|k+1} = (\underline{\boldsymbol{I}} - \underline{\boldsymbol{G}}_{k+1} \underline{\boldsymbol{H}}_{k+1})\, \underline{\boldsymbol{P}}_{k+1|k} \tag{11c}$$

$$\underline{\boldsymbol{\sigma}}_x \approx \quad 10\% \quad \frac{max\{\underline{\boldsymbol{x}}\} - min\{\underline{\boldsymbol{x}}\}}{2} \tag{12a}$$

$$\underline{\boldsymbol{\sigma}}_y \approx \quad 5\% \quad \frac{max\{\underline{\boldsymbol{y}}\} - min\{\underline{\boldsymbol{y}}\}}{2} \tag{12b}$$

$$\underline{\boldsymbol{\sigma}}_z \approx \quad 10\% \quad \frac{max\{\underline{\boldsymbol{x}}\} - min\{\underline{\boldsymbol{x}}\}}{2} \tag{12c}$$

E. Distributor and scaling

The distributor is also based on the principle of an observer. It requires a model of the system complement that estimates the system properties by observing its response. Since the model parameters for mapping system behaviour remain the same or change slowly, the soft coupling is suitable for compensating for latency times in the X-in-the-Loop environment.

$$\textbf{Prediction:} \quad \underline{\boldsymbol{x}}_{\mathrm{k+1|k}} = \underline{\boldsymbol{F}}^*_{\mathrm{k}} \underline{\boldsymbol{x}}_{\mathrm{k}} + \underline{\boldsymbol{B}}^*_{\mathrm{k}} \underline{\boldsymbol{u}}_{\mathrm{k}} \tag{13}$$

$$\textbf{Innovation:} \quad \underline{\boldsymbol{z}}^*_{\mathrm{k+1}} = \underline{\boldsymbol{y}}^*_{\mathrm{k+1}} - \underline{\boldsymbol{H}}^*_{\mathrm{k+1|k}} \underline{\boldsymbol{x}}^*_{\mathrm{k+1|k}} \tag{14}$$

$$\textbf{Distribution:} \quad \underline{\boldsymbol{x}}_{\mathrm{k+1|k+1}} = \underline{\boldsymbol{x}}_{\mathrm{k+1|k}} + \underline{\boldsymbol{G}}^*_{\mathrm{k+1}} \underline{\boldsymbol{z}}^*_{\mathrm{k+1}} \tag{15}$$

The distributor concept allows scaling between different systems. It is necessary if the parameters of the state space $\underline{\boldsymbol{F}}$ differs from a similar state space $\underline{\boldsymbol{F}}^*$. For instance, the brakes of the front and rear axle.

Since the state space matrices differ the state vector is predicted via the system matrix $\underline{\boldsymbol{F}}^*$ of the similar system. For scaling, the matrix $\underline{\boldsymbol{V}}^*$ is determined according to Eq. 17. For this purpose, the gain matrix $\underline{\boldsymbol{G}}^*$ is corrected. Consequently, the state vectror x of the similar system is predicted using the innovation $\underline{\boldsymbol{z}}^*$ from Eq. 14 and scaling matrix $\underline{\boldsymbol{V}}^*$.

$$\textbf{Prediction:} \quad \underline{\boldsymbol{x}}_{\mathrm{k+1|k}} = \underline{\boldsymbol{F}}^*_{\mathrm{k}} \underline{\boldsymbol{x}}_{\mathrm{k}} + \underline{\boldsymbol{B}}_{\mathrm{k}} \underline{\boldsymbol{u}}_{\mathrm{k}} \tag{16}$$

$$\textbf{Scaling:} \quad \underline{\boldsymbol{V}}^*_{\mathrm{k+1|k}} = \underline{\boldsymbol{F}}^*_{\mathrm{k}} \underline{\boldsymbol{F}}^{-1}_{\mathrm{k}} \underline{\boldsymbol{G}}^*_{\mathrm{k}} \tag{17}$$

$$\textbf{Distribution:} \quad \underline{\boldsymbol{x}}_{\mathrm{k+1|k+1}} = \underline{\boldsymbol{x}}_{\mathrm{k+1|k}} + \underline{\boldsymbol{V}}^*_{\mathrm{k+1|k}} \underline{\boldsymbol{z}}^*_{\mathrm{k+1}} \tag{18}$$

IV. Case Study

Experimental works in this study were carried out according to Fig. 2 and [9] to investigate the feasibility of globally distributed X-in-the-Loop environments. A full vehicle simulation located in Japan was used as a master to integrate a brake dynamometer located in Germany as a slave. A hardware-in-the-loop test bench was not used.

ABS braking test scenarios were used for the experimental verification and discussion of the X-in-the-Loop method, since they are challenging to map due to the highly dynamic processes. For controlling a PID method was used as the ABS algorithm. It is simply structured and allows a dedicated analysis. The associated parameters were determined using an optimization process and apply to the entire frequency spectrum. The reference slip λ_b results from a dedicated tire model.

The average round-trip time between the Master in Tokyo and the Slave in Ilmenau was $180\,ms$. For this reason the communication is not real-time capable, since the smallest time constant of the system was determined as $6.3\,ms$.

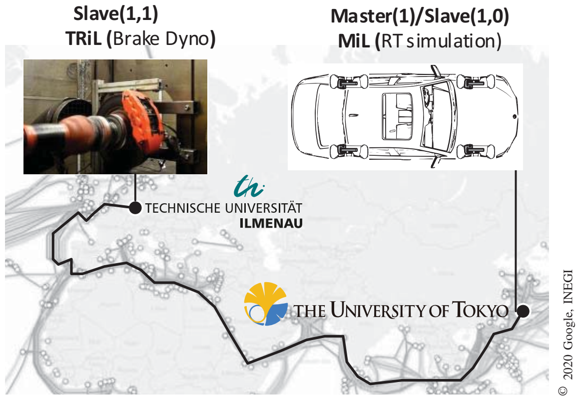

Fig. 3. Case study globally distributed X-in-the-Loop

A. Hard coupling

Due to the significant round trip time, the hard coupling technique introduces a latency time that is influencing the native behaviour of the braking system. As a result, the brake pressure modulation by the ABS controller becomes unstable and the system starts to oscillate.

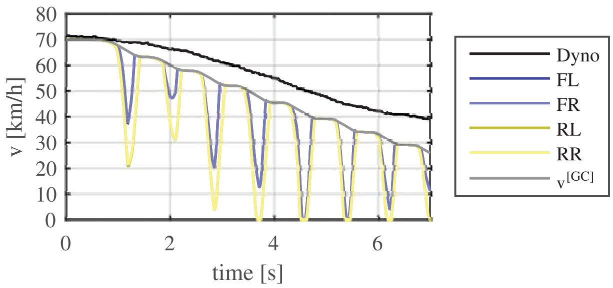

Fig. 4. Braking on low friction surface with ABS using hard coupling technique

B. Soft coupling

The observer-distributor concept was used for the smooth coupling of the flywheel brake test bench with the overall vehicle simulation. The braking torque was not directly fed back here, but a measured coefficient of friction was transferred indirectly via a model-based observer. In the next instance, the condition space model was corrected with the distributor and the conditions were distributed to each wheel. A predictor was not used.

In principle, the ABS control runs smoothly with a soft coupling, with no ABS intervention on the rear axle. Typically, the wheel speed on the front axle drops slightly during the first ABS cycle until the ABS intervenes.

Overall, it is possible to couple systems with each other over long distances using soft coupling technique without affect their native behaviour. The soft coupling of a globally distributed test environment thus corresponds to a hard coupling in a locally distributed test environment. The test results from

Fig. 5 represent the phenomena plausibly and can be validly used for testing brake systems of automated vehicle.

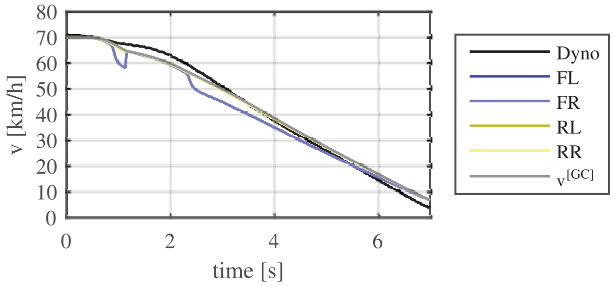

Fig. 5. Braking on low friction surface with ABS using soft coupling technique

C. Prediction

In synergy with the soft coupling method, time-delayed states can be predicted using prediction methods. Fig. 6 shows a prediction excerpt of the brake torque measured on the brake dynamometer. Thereby the time synchronous state $y(t)$ is received as $y(t - \tau_d)$ delayed by the communication. The states can be predicted despite the large latency and the large jitter. The estimated prediction $y(t|t-\tau_d)$ is in phase with the time synchronous state $y(t)$.

However, the used second-order Smith predictor cannot correctly predict the amplitudes in the case of sudden changing states. This causes overshoots for large curved waveforms. The prediction of homogeneous and slowly changing states, such as the speed, matching the time synchronous signal. Beyond, the initial states at the start of the observation cannot be predicted, since the first information on the prediction is available time delayed. For these reasons, a higher order of the predictor is required for highly dynamic systems. However, the choice of a higher order is recommended with restrictions, since each derivativation induces numerical errors and noise. Smith predictors with lower order introduces instabilities which affects the native behavior.

Despite the jittering round-trip time, it could be proved that it is valid to assume a constant latency for prediction. However, only a time delay can be compensated with the predictor. For physical synchronization, the predictor must be combined with the soft coupling method.

V. Conclusion

The experimental results show that the X-in-the-loop method is robust against disturbances and uncertainties. In order to verify the robustness, experimental brake tests with ABS were carried out. The focus was not on the development of ABS. Instead, a simplified implementation of a continuous ABS was used. It induces a wide range of transient effects and requires a high-performance test environment to map the effect chain.

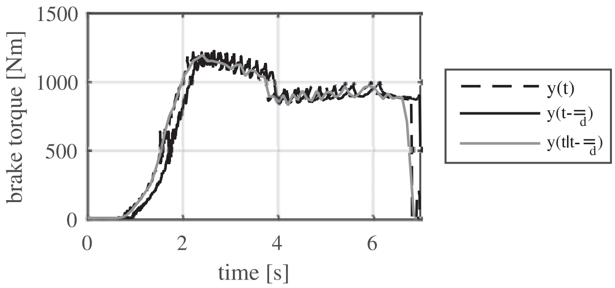

Fig. 6. Braking on low friction surface with ABS using soft coupling technique

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