Development and Validation of a Remote-Controlled Test Platform for Bicycle Dynamics

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1 INTRODUCTION

Through the electrification of bicycles, the implementation of new active and passive safety systems becomes possible. Examples for such systems are bicycle ABS [1], TU Delft – Fall Prevention Bicycle [2], Bosch Help Connect (eCall System for bicycles) [3], airbag helmets [4] and many others. One of the main difficulties in developing and testing such safety systems is, that test riders should not be exposed to high risks when testing early prototypes. Thus, an automated or remote-controlled test platform for the analysis of bicycle dynamics and for testing of newly developed safety systems could boost the development of such systems and make it safer.

The main difficulty when developing such a test platform, which has been addressed in this work, is stabilizing it at low speeds (1.5 m/s – 4.5 m/s) and being capable of tracking a desired yaw rate, only using a steer actuator. In the following, the development of such a test platform is described and first experimental results are presented.

2 MODEL

While for simulations, one can use quite complex nonlinear bicycle models, which are mostly based on the Carvallo-Whipple model [5], [6], for controller design and analysis much simpler models are necessary. Such a simplified nonlinear model was introduced by Getz [7] and is used for controller design in this work. In this simplified model, the four bodies of the Carvallo-Whipple Model are reduced to two bodies, tire radiuses are set to zero, inertias are neglected and steer rate and roll torque are used as inputs for the lateral dynamics (see Figure 1). After linearizing around the origin and setting the roll torque to zero since it is not needed for controller design, the model equations are given as

$$\begin{pmatrix} \dot{\varphi} \\ \ddot{\varphi} \\ \dot{\delta} \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 \\ -\frac{g}{z} & 0 & \frac{v^2}{l\,z} \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} \varphi \\ \dot{\varphi} \\ \delta \end{pmatrix} + \begin{pmatrix} 0 \\ \frac{x\,v}{l\,z} \\ 1 \end{pmatrix} u_{\delta}. \tag{1}$$

The states of the systems are roll angle φ, roll rate $\dot{\varphi}$ and steer angle δ and the control input is the steer rate u_{δ}. For the parametrization of the model, only four bicycle parameters are needed, namely the wheelbase l, the x- and z-position of the center of gravity and the (constant) velocity v. For small angles, the yaw rate $\dot{\psi}$ of the bicycle can be approximated by

$$\dot{\psi} = \delta\, v/l. \tag{2}$$

In the simplified model, many properties of the full model are no longer depicted (for example self-stability in a certain speed range), but it still includes the basic bicycle dynamics which are necessary for controller design.

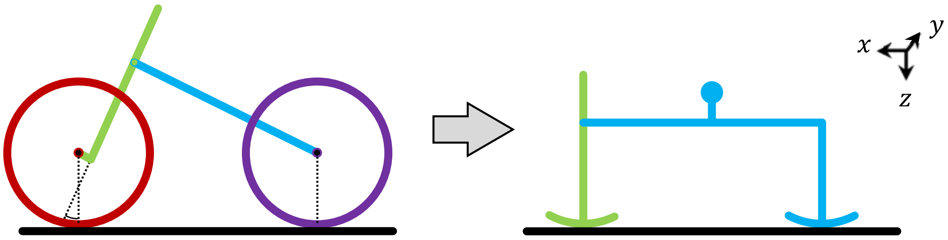

Figure 1: *Reduction of the four-body model to the simplified two-body model*

3 CONTROLLER

Due to the simplifications, on the bicycle model, it is necessary, to design a controller, that has some robustness properties. There are different options, but because of its simple design and simple implementation, an LQR state feedback controller is chosen.

Since the bicycle shall not only be stabilized, but also should follow a reference yaw rate $\dot{\psi}_{\mathrm{ref}}$, it is necessary to add some feedback of the (integrated) yaw rate tracking error. Hence, the state vector is augmented by the integrated yaw rate tracking error ξ. The augmented system is given as

$$\begin{pmatrix} \dot{\varphi} \\ \ddot{\varphi} \\ \dot{\delta} \\ \dot{\xi} \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 & 0 \\ -\frac{g}{z} & 0 & \frac{v^2}{l\,z} & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -\frac{v}{l} & 0 \end{pmatrix} \begin{pmatrix} \varphi \\ \dot{\varphi} \\ \delta \\ \xi \end{pmatrix} + \begin{pmatrix} 0 \\ \frac{x\,v}{l\,z} \\ 1 \\ 0 \end{pmatrix} u_{\dot{\delta}}. \tag{3}$$

The Complete control loop including the yaw rate tracking error feedback is shown in Figure 2. The control gains are speed dependent and are calculated using LQR control theory.

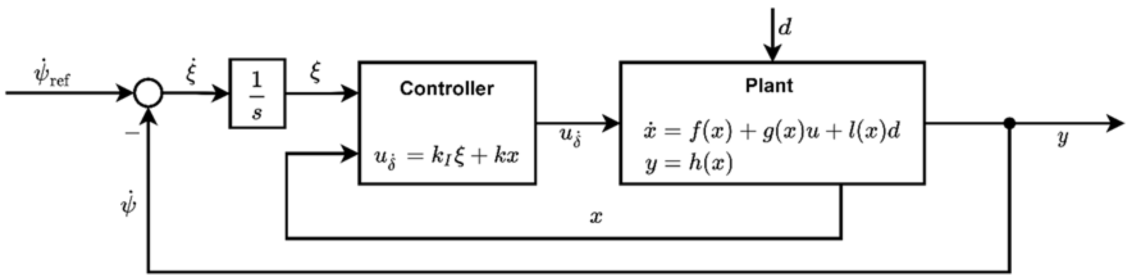

Figure 2: *Control loop of the augmented system*

4 SIMULATIONS AND EXPERIMENTAL RESULTS

Simulations of the proposed control strategy have been made using a modified version of the full bicycle model to allow for steer rate inputs. Additionally, the simulation model includes sensor models and a state estimator to recover the full state vector from the sensor signals. Since simulations show similar results to the experiments, only experimental results of the following two riding scenarios at a constant velocity of $v = 2.5\ \mathrm{m/s}$ are presented in this abstract:

1. Straight motion with pulse-like disturbance at $t_1 = 6\mathrm{s}$ and $t_2 = 12.6\mathrm{s}$.
2. Straight motion with a turn command ($\dot{\psi}_{\mathrm{ref}} = 0.5\mathrm{rad/s}$) at $t_1 = 8\mathrm{s}$.

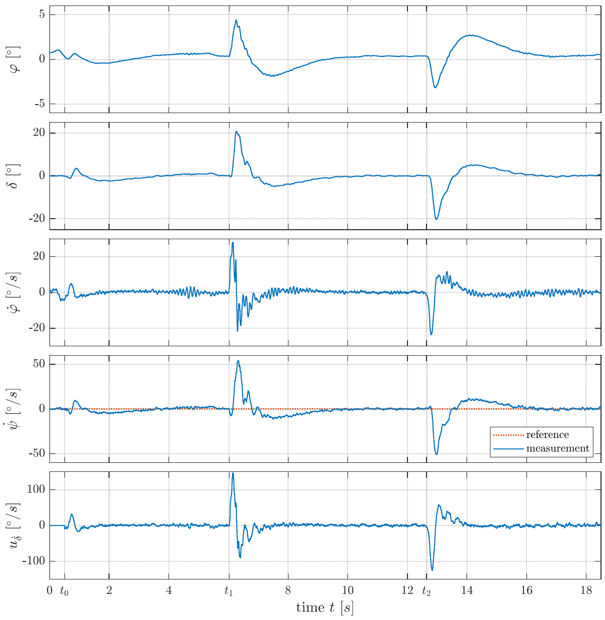

***Figure 3:** Experimental results of driving scenario 1*

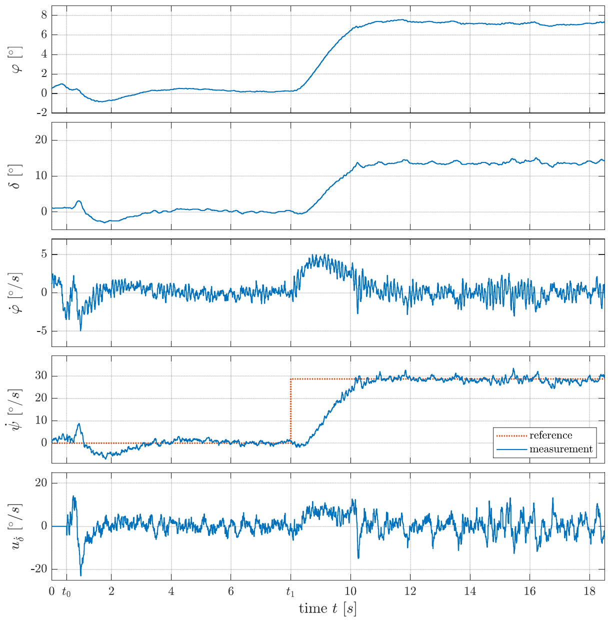

***Figure 4:** Experimental results of driving scenario 2*

The results of the experiments can be seen in Figure 3 and Figure 4. Both measurements start with a part, in which the bicycle is accelerated to the desired speed and in which the lateral dynamics controller is not yet active. As soon as the bicycle reaches the desired speed (at time t_0), the controller is activated and stabilizes the bicycle. The first measurement shows that the bicycle can track a straight line and quickly recovers from disturbances. In the second measurement, tracking a reference yaw rate is demonstrated. It can be observed that the bicycle is again stabilized and follows the desired yaw rate well.

5 CONCLUSION

Development of a remote-controlled bicycle test platform will help developing new safety systems. Our work lays the foundation for building such a platform by providing a method for simultaneously stabilizing a bicycle and tracking a desired yaw rate using a steer actuator. By using a very simple model and by using steer rate as a control input, the stabilization system can be easily adapted to various bicycles (only few parameters need to be known). On the other hand, due to the use of the steer rate as a control input, the reactions to disturbances and setpoint changes (of the yaw rate) are somewhat slow and the bike cannot be used to investigate disturbances to the steering.

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