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Dynamics and Control of a Steer-by-Wire Bicycle

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ABSTRACT

This work is focused on the modeling and experimental validation of a steer-by-wire system for bicycles. The purpose for this system is to modify and enhance the lateral stability of a bicycle at low forward speeds. Case studies show additional capabilities of a steer-by-wire system on bicycles to influence its dynamic behavior, by providing a dynamic response comparable to a bicycle with a virtually different geometry or even the ability to stabilize an inherently unstable bicycle. A steer-by-wire bicycle prototype was designed and build by replacement of the mechanical connection between handlebar- and steering-assembly by electronic actuators and a custom digital controller. The steer-by-wire bicycle prototype equipped with sensors, measuring the forward speed and roll-rate was subsequently used to experimentally evaluate the proposed control algorithms. Preliminary rider tests showed a perceived near-to-identical behaviour of the steer-by-wire system to a mechanical connection. Adding lateral stability enhancement at low speed by active steer-torque control was perceived as beneficial by the rider.

Keywords: bicycle, steer-by-wire, stability, control, rider control.

1 INTRODUCTION

Already for some time, electronic enhancements regarding vehicle behavior has made its way into the aviation and automotive industry by the term ”by-wire” technology. Electronic sensors and actuators are used to replace traditional mechanical systems in which software is used to operate the actuators in a way that is not possible with traditional mechanical systems.

The use of steer-by-wire technology can also offer great opportunities on single-track vehicles like motorcycles, scooters and bicycles. Single-track vehicles can be laterally highly unstable, especially at low forward speeds and they require a relative high amount of rider control [1, 2]. By replacing the mechanical connection between the handlebar- and steering-assembly with electronic actuators and adding sensors to measure the state of the system, a controller can be used to control the dynamic behavior of the bicycle.

In open literature there is no research available which experimentally evaluates a steer-by-wire system on single-track vehicles. Only a few theoretical publications proposing enhancements in motorcycle handling [3, 4] are available. It remains questionable if the removal of the counter steering behavior as proposed by Marumo and Nagai [3] will be beneficial. The possibility of a lane keeping assistance system on motorcycles by Katagiri *et al.* [4] on the other hand can greatly improve safety. This is also demonstrated by Seiniger *et al.* [5] by actively assisting the motorcycle rider's steer input to hold its driving path during extensive in-corner braking manoeuvres.

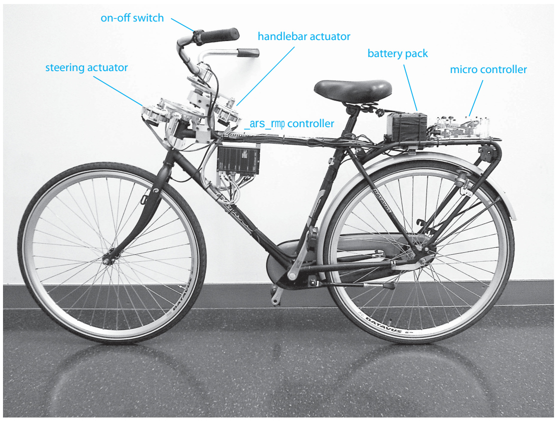


FIGURE 1. Prototype of the steer-by-wire bicycle with steering and handlebar actuators, sensors, actuator controllers, battery pack and microcontroller.

The work presented here, is focused on the modeling and experimental validation of a steer-by-wire control strategy to modify and enhance the lateral stability of a bicycle at low forward speeds. Case studies show additional capabilities of a steer-by-wire system on bicycles to influence its dynamic behavior, by providing a dynamic response comparable to a bicycle with a virtually different geometry or even the ability to stabilize an inherently unstable bicycle. A steer-by-wire bicycle prototype was designed and build by replacement of the mechanical connection between handlebar- and steering-assembly by electronic actuators and a custom digital controller, see Figure 1. The steer-by-wire bicycle prototype equipped with sensors, measuring the forward speed and roll-rate is subsequently used to experimentally evaluate the proposed control algorithms.

The paper is organized as follows. After this brief introduction the model for the system design is described and some simulation results are shown. Next the experimental setup is described and some preliminary test results are shown. The paper ends with some conclusions.

2 SYSTEM DESIGN AND SIMULATION

The model for the steer-by-wire system design is based on the three degree of freedom Whipple/Carvallo [1] bicycle model. This model is extended by separating the handlebar assembly from the front steering assembly, which introduces an additional rotational degree of freedom, see Figure 2. The lateral degrees of freedom of this extended model are: the rear frame roll angle ϕ, the front assembly steering angle δ, and the handlebar steering angle θ. Since we are only interested here in the lateral dynamics, the forward speed v, which is a degree of freedom of the Whippel/Carvallo model, is treated as a parameter. Combining the lateral degrees

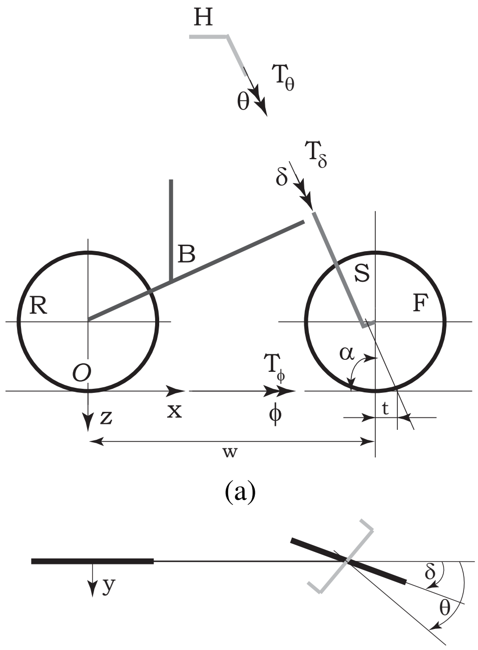


FIGURE 2. Steer-by-wire bicycle model, side view (a) and top view (b), together with the lateral degrees of freedom, rear frame roll angel ϕ, front frame steering angle δ, and handlebar steering angle θ, and some geometry variables. This model, based on the Whipple/Carvallo bicycle model [1], shows the addition of a separate handlebar body H and the possibility to have unequal front wheel steering δ and handlebar θ relations.

of freedom in a generalized coordinate vector $\mathbf{q} = [\theta, \phi, \delta]^T$, the linearized equations of motion for the extended bicycle model can be expressed by

$$\bar{\mathbf{M}}\ddot{\mathbf{q}} + \bar{\mathbf{C}}\dot{\mathbf{q}} + \bar{\mathbf{K}}\mathbf{q} = \bar{\mathbf{f}}, \quad (1)$$

with the mass matrix $\bar{\mathbf{M}}$, damping matrix $\bar{\mathbf{C}}$ and stiffness matrix $\bar{\mathbf{K}}$ given by,

$$\bar{\mathbf{M}} = \begin{bmatrix} I_\theta & 0 \\ 0 & \mathbf{M} \end{bmatrix}, \qquad \bar{\mathbf{C}} = \begin{bmatrix} 0 & 0 \\ 0 & v\mathbf{C1} \end{bmatrix},$$
$$\bar{\mathbf{K}} = \begin{bmatrix} 0 & 0 \\ 0 & g\mathbf{K0} + v^2\mathbf{K2} \end{bmatrix}, \tag{2}$$

and the right-hand side forcing term $\bar{\mathbf{f}} = [T_\theta, T_\phi, T_\delta]^T$, which contains the handlebar torque T_θ, the rear frame roll torque T_ϕ (usually zero), and the front steering assembly torque T_θ. The matrices $\mathbf{M}$,$\mathbf{C1}$,$\mathbf{K0}$, and $\mathbf{K2}$, are the two-by-two matrices from the linearized equations of motion of the original Whipple/Carvallo model [1], I_θ is the mass moment of inertia of the handlebar assembly, v is forward speed and g is the gravitational acceleration.

2.1 Handlebar tracking control

To minimize the difference between the handlebar angle θ and the steering assembly angle δ, tracking control needs to be implemented. In this way the steer-by-wire system should behave like an ordinary, mechanically steered bicycle, when the rider applies a steer torque at the handlebar. A proportional-differential (PD) controller is implemented which provides an action-reaction torque T_{PD} to the steering assembly and the handlebar, of the form,

$$T_{PD} = K_p(\theta - \delta) + K_d(\dot{\theta} - \dot{\delta}), \tag{3}$$

with proportional gain K_p, and differential gain K_d. The forcing term in 1 then becomes,

$$\bar{\mathbf{f}} = \begin{bmatrix} T_\theta \\ T_\phi \\ T_\delta \end{bmatrix} = \begin{bmatrix} T_h - T_{PD} \\ 0 \\ T_{PD} \end{bmatrix}, \tag{4}$$

with the rider applied steer torque T_h at the handlebar, and zero applied roll angle torque. The steer-by-wire bicycle model can be visualized in a block diagram as shown in Figure 3. The handlebar block represents the rotational inertia of the handlebar while the controller block represents the tracking controller layout. For the PD-controller, the proportional and differential gains in 3 are chosen such that a critically damped system response is obtained to ensure a fast and accurate response without overshoot.

As an example we use the parameters of the benchmark bicycle [1], with a handlebar inertia of $I_0 = 0.001$ kgm^2, proportional gain $K_p = 90$ Nm/rad, and differential gain $K_d = 0.6$ Nms/rad. The performance of this tracking control is shown in Figure 4 by comparing the steer stiffness transfer functions of the benchmark bicycle without and with the steer-by-wire system. The steer stiffness transfer function is defined as $H_{BB}(s) = T_\delta(s)/\delta(s)$ for the rigid connection and as $H_{SBW}(s) = T_\theta(s)/\theta(s)$ for the steer-by-wire bicycle. The proposed system shows, in a forward speed range of 0 to 10 m/s, good tracking performance in a frequency range of 0 to 3 Hz. Above 3 Hz the steer stiffness drops of due to the finite bandwidth of the tracking system.

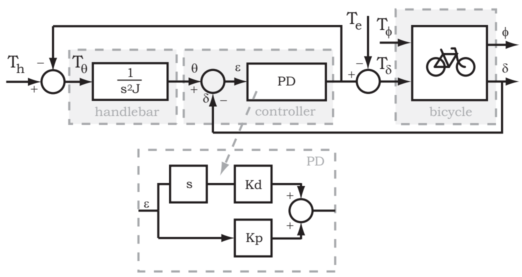
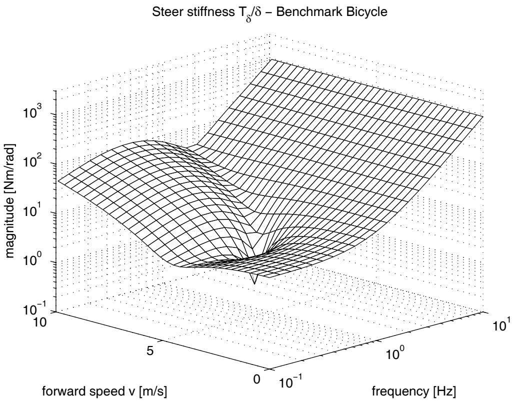


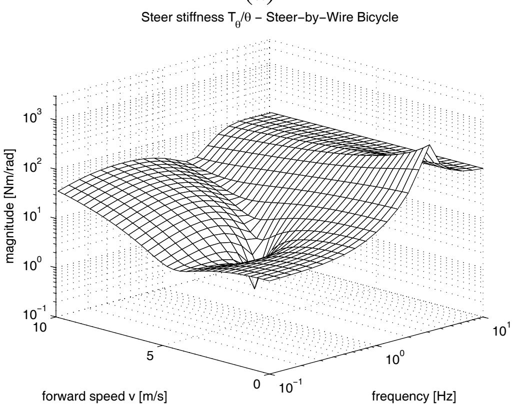
FIGURE 3. Block diagram of the steer-by-wire bicycle model, which includes the handlebar tracking controller (PD) and steer torque feedback to the handlebar, with the rear frame roll angle ϕ, front assembly steering angle δ, handlebar steering angle θ, by the rider applied handlebar steering torque T_h, front assembly steering torque T_δ, and the handlebar tracking controller and handlebar feedback steer-torque T_{PD}.

2.2 Lateral stability enhancement

The unstable lateral motions at low speed can be stabilized by adding a steer-torque control system to the handlebar tracking control system. For the design of the low speed stability controller we follow the work of Ruijs and Pacejka [6] who proposed a steer-into-the fall controller [2] for a motorcycle robot at sub-weave speed, which uses the roll rate of the rear frame as input and steer-torque as system output, with linear regressive gain scheduling as a function of forward speed. This controller has successfully



(a)



(b)

FIGURE 4. Magnitude of the steer stiffness transfer function, as perceived by the rider, as a function of forward speed v and the frequency s, (a) on the benchmark bicycle $H_{BB}(s)$, and (b) the steer-by-wire bicycle $H_{SBW}(s)$. The steer stiffness at the handlebars changes significantly as a function of input frequency as well as the forward speed of the bicycle. At higher frequencies the steer stiffness is primarily defined by the mass- and inertia properties of the bicycle. A significant drop in the steer stiffness magnitude relation occurs at the weave speed ($v_w = 4.29$ m/s) and the corresponding weave frequency (0.55 Hz) of the bicycle shown by the downward resonance-like peak. The steer stiffness of the steer-by-wire bicycle at higher frequencies are primarily defined by the stiffness and damping properties of the PD-controller, whereas the anti-resonance-like upward peak at low forward speeds is caused by the PD-controller coefficients and the mass- and inertia properties defined in the system matrix.

been implemented [7] on the benchmark bicycle model and on scaled down prototype [8]. The proposed stabilizing control takes on the form of an additional steer torque T_{SE} applied at the steering assembly,

$$T_{SE} = K_s(v_{avg} - v)\dot{\phi} \quad \forall \quad v < v_{avg} \tag{5}$$

which is proportional to the rear frame roll rate $\dot{\phi}$, the forward speed v of the bicycle, and a constant K_s. The magnitude of this speed dependency is linearly decreased in magnitude up to v_{avg}, which is around the weave speed, as no stabilizing control is required inside the auto-stable speed region. At higher forward speeds no stabilizing control torque is applied, as the unstable capsize mode is relatively slow and easy to control. The forcing term in the linearized equations of motion (1) is now $\bar{\mathbf{f}} = [T_h - T_{PD}, 0, T_{PD} + T_{SE}]^T$. This leads to an extended block diagram for the complete system, as shown in Figure 5.

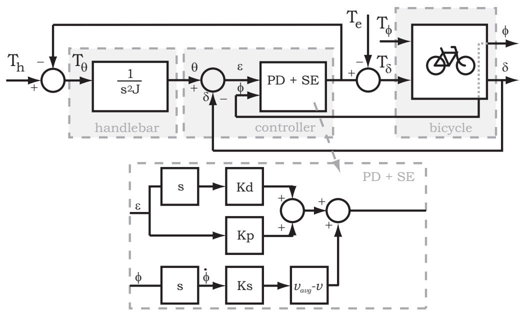
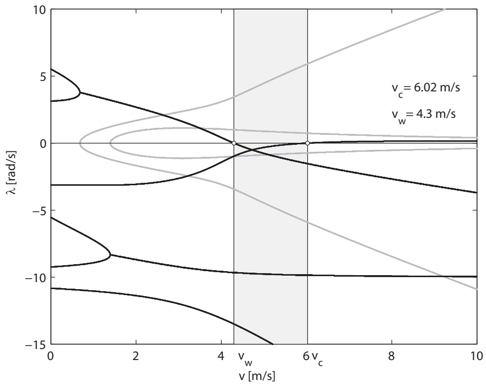


FIGURE 5. Block diagram of the steer-by-wire bicycle model with enhanced lateral stability at low speed, which includes the combined handlebar tracking controller (PD) and low speed stabilization controller (SE).

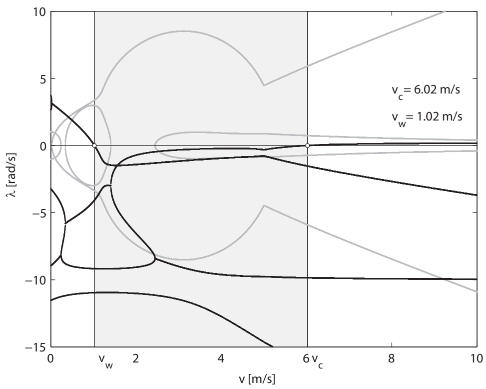
By applying this low speed stabilization controller with proportionality constant $K_s = 10$ Ns^2/rad and $v_{avg} = 5$ m/s, the weave speed is decreased from 4.3 m/s to 1.0 m/s and by such making the bicycle self-stable from 1 m/s until high forward speed, since the unstable capsize mode is relatively slow and easy to control. This change in the eigenvalues and the selfstable speed range is illustrated in Figure 6.

3 EXPERIMENTAL SETUP

A conventional Dutch city bicycle (Batavus Browser) is converted to a steer-by-wire bicycle by replacement of the mechanical steering connection with electronic actuators and sensors,

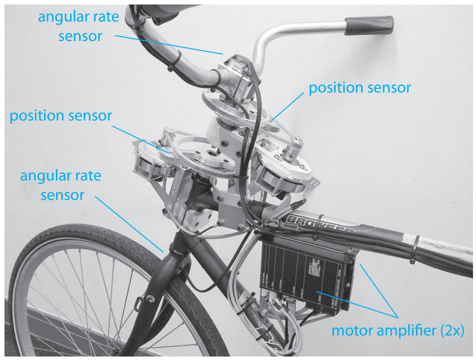


(a)

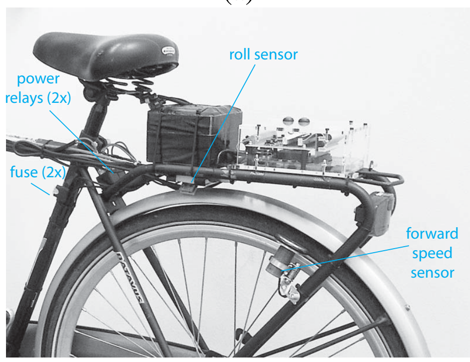


(b)

FIGURE 6. Eigenvalues λ from the linearized stability analysis for the original steer-by-wire benchmark bicycle model (a) in comparison to the eigenvalues for the same model with added lateral stability control (b), in the forward speed range of $0 < v < 10$ m/s. The lateral stability control enlarged the stable forward speed range by pushing the weave speed v_w back from 4.3 to 1.0 m/s, while retaining the capsize speed v_c.



(a)



(b)

FIGURE 7. Steer-by-wire bicycle component layout, showing the physical placement of the steering- and handlebar assembly, battery pack and controller, with (a) front assembly with sensors, motors, and motor amplifiers, and (b) rear rack with battery pack, microcontroller, and forward speed sensor.

see Figure 1. Two identical Maxon EC90 brushless DC motors and EPOS2 power-amplifiers actuate the steering- and handlebar-assembly, as shown in Figure 7. To increase the maximum output torque, the actuators are connected using a timing-belt construction with an amplification ratio of $132/20$ which allows for a maximum instantaneous steer torque of about 15 Nm. Separate Altheris FCP22AC position- and Silicon Sensing CRS03 angular rate sensors are used on the handlebar- and steering assembly to provide the controller the required state information. The roll sensor uses an InvenSense IDG-500 angular rate gyro to measure the rear frame roll rate. A small Maxon DC motor, spring-loaded against the rear wheel is used to measure the forward speed of the bicycle. A Microchip dsPIC33F equipped Explorer16 micro-controller is used to control the system. A 24 V Super-B lithium-ion battery pack powers the actuators and micro-controller.

The proposed PD-controller values of $K_p = 90$ Nm/rad and $K_d = 0.6$ Nms/rad of the benchmark bicycle simulation would in practice result in unrealistic high actuator torques. Also, during the experiments it became apparent that presumable un-modeled actuator- and controller dynamics cause the handlebar assembly to become mildly unstable.

The steer-by-wire prototype subsequently utilizes a double PD-controller configuration with slightly lower and unequal gain coefficients. The double PD-controller configuration, one in the steer torque path ($K_p = 15$ Nm/rad, $K_d = 1.5$ Nms/rad) and one in the handlebar torque path ($K_p = 8$ Nm/rad, $K_d = 0.6$ Nms/rad), was used to maximize the feedback torque and tracking performance without forcing the handlebar assembly into an unstable mode.

4 PRELIMINARY TEST RESULTS

Preliminary rider tests with the steer-by-wire system showed very satisfactory behaviour of the system. After gaining some confidence, the rider could not distinguish the handling of the steer-by-wire bicycle from a bicycle with rigid steering connection. Only when looking at the front steering assembly while applying a rider steering torque, the rider was able to see a small phase lag between the handlebar and the steering assembly. This small phase lag had no influence on he perceived handling during normal operation.

More qualitative results were obtained with the stability enhanced steer-by-wire bicycle. In riding a straight track at low forward speed at 5 km/h (1.4 m/s), two cases were compared; with and without lateral stability enhancement. During these tests the steer rate of the handlebar was recorded as a measure for rider control input. Figure 8 shows the power spectral density (PSD) of the steer rate. As a measure of steer effort, the area under the PSD curve, indicated by Pe, is used. Clearly, steer effort without haptic feedback (Pe = 2890) is much larger than with haptic feedback (Pe = 980). Moreover, the power spectral density of the stability enhanced bicycle at low forward speed (5 km/h) was shown to be comparable to the PSD at normal forward speed of 20 km/h (not shown here). This clearly indicates the benefit of such a stability enhancement system at low forward speed. Rider steer effort at low speed is reduced which makes the bicycle more easy to ride and could lead to future implementation on bicycles tailored for elderly or those physically impaired.

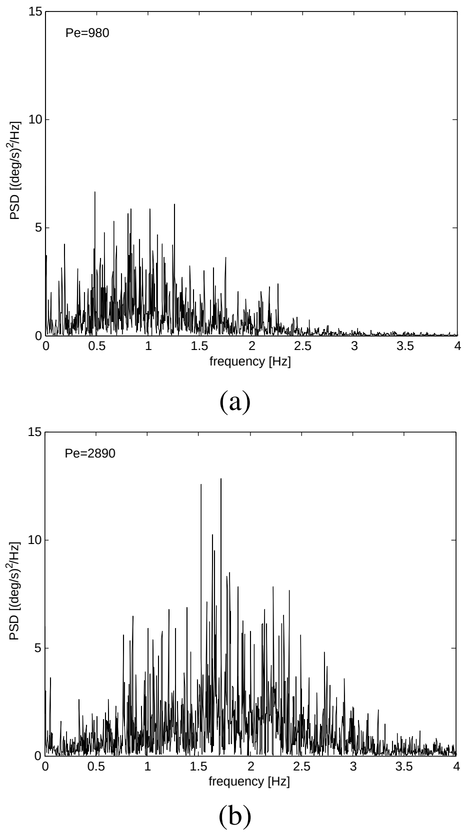


FIGURE 8. Power spectral density (PSD) of the handlebar steer rate for a bicycle with (a) regular steer torque feedback and (b) no steer torque feedback on the handlebar, riding a straight track at a forward speed of 5 km/h. As a measure of steer effort, the area under the PSD curve, indicated by *Pe*, is used. Clearly, steer effort without haptic feedback ($Pe = 2890$) is much larger than with haptic feedback ($Pe = 980$).

5 CONCLUSIONS

A steer-by-wire bicycle has been designed and build. Preliminary rider tests showed a perceived near-to-identical behaviour of the steer-by-wire system to a mechanical connection. Adding lateral stability enhancement for low speed stability by active steer-torque control reduced the steer-effort of the rider considerably and was perceived as beneficial by the rider.

In future research the steer-by-wire bicycle will serve as a versatile experimental platform for identifying human rider control in bicycling.

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