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Design and experimental validation of a haptic steering interface for the control input of a bicycle simulator

A. L. Schwab[1] and Antonio M. Recuero[2]

[1]Laboratory for Engineering Mechanics
Delft University of Technology
Mekelweg 2, NL-2628 CD Delft, The Netherlands
a.l.schwab@tudelft.nl

[2] Department of Mechanical and Materials Engineering
University of Seville
Camino de los Descubrimientos, s/n, 41092, Seville, Spain
amrecuero@us.es

Abstract

In this work a bicycle simulator, in which the rider drives a monitored handlebar and receives realistic visual feedback and haptic feedback torques on the handlebar from the computer model of the bicycle, is described and utilized. Riders can be asked to follow prescribed trajectories while having diverse visual and haptic cues. This experiment setup can help understand the synergy among the parts intervening in the active stabilizing process in bicycling. Discussion and conclusions are parts of this paper. **Keywords:** *bicycle, simulator, dynamics, haptic feedback, real time*

1 Introduction

Bicycle dynamics has been studied for more than a century using rigid body dynamics but it has not been until recent times that a three degree of freedom bicycle model, comprising 25 design parameters, has been benchmarked and its self-stability ascertained [1]. A forward speed range in which the upright position of bicycles in straight trajectory is usually self-stable is found out. Within this range the rider does not need to actuate the bicycle very actively to ride safely due to the bicycle's self-stability. This is also the case for some steady circular motions [16]. In these works, the rider's passive contribution to bicycle dynamics is considered to be inertia attached to rear frame. Different postures can be adopted by the rider depending on the style of riding or type of bicycle. The upper body can lean forward with stretched arms on the handlebar or remain upright with flexed arms. These variations change the vehicle self-stability and have consequences on controllability. For both postures, steer torque control can stabilize the bicycle for unstable modes and shows significant better modal controllability (ease to balance the vehicle) than lean torque control [5].

It is common knowledge that skilled riders can stabilize the bicycle at low speeds, i.e., experienced riders can exert a stabilizing steering torque when certain unstable mode dominates bicycle dynamics [6]. In order to do so, they use haptic, vestibular and visual information. Since the rider's output, according to recent experimental studies, could be considered to be mostly a torque on the handlebar [17], he must combine sensory information to carry out the proper stabilizing action.

Haptics technologies have opened up a new field of possibilities in Engineering with broad applications [10]. Among them, educational-aimed research may be emphasized [12]. When sensory information come from a single entity, humans integrate visual and haptic information in an optimal way, i.e., reducing the variance of the final estimate of the object property [2]. Nevertheless, the single-cue information is not lost when the brain utilizes diverse sensory information to make the estimation. On the contrary, this information is available to identify odd stimuli [15], i.e., to distinguish the quality of sensory inputs. These aspects are of importance in the stabilizing action of the rider since the driving of the vehicle and its stabilization must be performed at the same time.

In this work it is aimed to construct a bicycle simulator based on benchmark bicycle equations of motion [**?**] in which the rider interacts with the virtual bicycle via handlebar dynamics and perceives the trajectory and bicycle roll angle by means of first or second person views form a computer display. From the equations of motion of the bicycle a haptic feedback torque is generated end applied to the handlebar such that the rider feels a certain amount of torque. Through haptic and visual interactions conclusions regarding the need for sensory information to balance the bicycle could be drawn.

This paper is organised as follows. After this brief introduction technical requirements are discussed. Next, the equations of motions used in the bicycle simulator ar presented, after which the dynamics of the bicycle simulator is discussed. Then the bicycle simulator setup is presented. The paper ends with some preliminary results and a short conclusion.

2 Technical requirements and simulator performance.

Haptic systems in vehicle dynamics are usually connected with two types of realities. One current application of kinesthetic devices is focused on enabling the driver to feel feedback from the vehicle state when steer-by-wire systems come into play. Steer-by-wire vehicles often need a resistance torque to prevent excessive rotation of the steering wheel. This feedback torque is in many cases defined by simple relations as functions of wheel angle, wheel torque or vehicle state, and aims to assist the driver in achieving the desired trajectory in real performance [9]. Similarly, Haptics can also be used as a tool to improve first stages of task learning through fading guidance towards a goal [13]. On the other hand, computer simulations with virtual environments can be helpful to evaluate different strategies for steering control [8], as a previous stage to its implementation, and develop control systems aimed to improve riding safety [7].

In the present work the rider interacts with a virtual environment, receiving realistic handlebar torque from a bicycle model. Stability of the haptic system for any kind of human contribution, e.g., tight grasp or sudden release, must be guaranteed. In so doing, one can resort to place a "virtual coupling" between the haptic device and the virtual environment that acts as a mechanical filter [4]. The bicycle haptic interface, as explained in following sections, shows a impedance casuality, i.e., forces are transmitted to the rider, whereas the input of the virtual environment is the handlebar state. Uncertainties in the measurement of steering angle and its rate may lead, depending on the physical model utilized, to unrealistic fed back torque or excessive phase lag [14]. The set of sample rates of sensors and the model is another key factor in the haptic system. It must be high enough to keep a pleasant refreshing rate of the simulator visualization and results in natural and smooth feeling in rider's limbs.

3 Bicycle simulator equations of motion

The core of the bicycle simulator are the linearized equations of motion of the Whipple/Carvallo bicycle model, which recently has been benchmarked by Meijaard *et. al* [1]. These linearized equations of motion for a bicycle in the upright position are defined in terms of the rear frame roll angle, ϕ, and the front assembly steer angle, δ, as follows:

$$\mathbf{M}\ddot{\mathbf{q}} + v\mathbf{C}_1\dot{\mathbf{q}} + \left[g\mathbf{K}_0 + v^2\mathbf{K}_2\right]\mathbf{q} = \mathbf{f}, \tag{1}$$

where $\mathbf{q} = [\phi \ \ \delta]^T$, $\dot{\mathbf{q}} = [\dot{\phi} \ \ \dot{\delta}]^T$ and $\ddot{\mathbf{q}} = [\ddot{\phi} \ \ \ddot{\delta}]^T$, stand for the generalized coordinates, velocities and accelerations, respectively; $\mathbf{M}$ is the mass matrix, and the damping matrix, $\mathbf{C} = v\mathbf{C}_1$, and the stiffness matrix, $\mathbf{K} = g\mathbf{K}_0 + v^2\mathbf{K}_2$, are shown as explicit functions of the bicycle forward velocity, v, and the acceleration of gravity, g, as defined in [1]. The vector $\mathbf{f}$ denotes the system external generalized forces. From now on, the following simpler form of the equations will be used:

$$\mathbf{M}\ddot{\mathbf{q}} + \mathbf{C}\dot{\mathbf{q}} + \mathbf{K}\mathbf{q} = \mathbf{f}. \tag{2}$$

The matrix form of Eq. (2) when only an input torque T_δ at the handlebar is applied can be written as,

$$\begin{bmatrix} M_{\phi\phi} & M_{\phi\delta} \\ M_{\delta\phi} & M_{\delta\delta} \end{bmatrix} \begin{bmatrix} \ddot{\phi} \\ \ddot{\delta} \end{bmatrix} + \begin{bmatrix} C_{\phi\phi} & C_{\phi\delta} \\ C_{\delta\phi} & C_{\delta\delta} \end{bmatrix} \begin{bmatrix} \dot{\phi} \\ \dot{\delta} \end{bmatrix} + \begin{bmatrix} K_{\phi\phi} & K_{\phi\delta} \\ K_{\delta\phi} & K_{\delta\delta} \end{bmatrix} \begin{bmatrix} \phi \\ \delta \end{bmatrix} = \begin{bmatrix} 0 \\ T_\delta \end{bmatrix}, \tag{3}$$

where ϕ is the roll angle of the frame and δ denotes the handlebar angle. Since in this work the rider is not allowed to directly contribute to roll angle dynamics, no approximation has been made in Equation (3).

The input of the system is the steer torque T_δ exerted by the rider on the handlebar. Measuring this torque accurately is problematic, because the rider also exerts torques in the other two directions by leaning on the handlebar. These other torques tend to be an order higher in magnitude than the steer torque and therefore give rise to cross-over in the measurement of the steer torque. Instead, we measure the steer angle δ and steer angular rate $\dot{\delta}$. These angles are input for the bicycle simulator model. The output is then the motion of the bicycle and the haptic feedback torque on the handlebar.

The first equation can be integrated for ϕ if one takes advantage of the knowledge of δ and $\dot{\delta}$ through direct measurements on the real handlebar. We do not measure the steer angle acceleration, $\ddot{\delta}$, because steer angle accelerations are low and measurements tends to be very noisy. Hence, the term with $\ddot{\delta}$ is disregarded in the roll angle equation. The roll angle equation of (3) is then reduce to,

$$M_{\phi\phi}\ddot{\phi} + C_{\phi\phi}\dot{\phi} + K_{\phi\phi}\phi = -\left(\cancel{M_{\phi\delta}\ddot{\delta}} + C_{\phi\delta}\dot{\delta} + K_{\phi\delta}\delta\right), \tag{4}$$

where the coordinate ϕ can be integrated from initial conditions like a one-degree-of-freedom system. In this approach

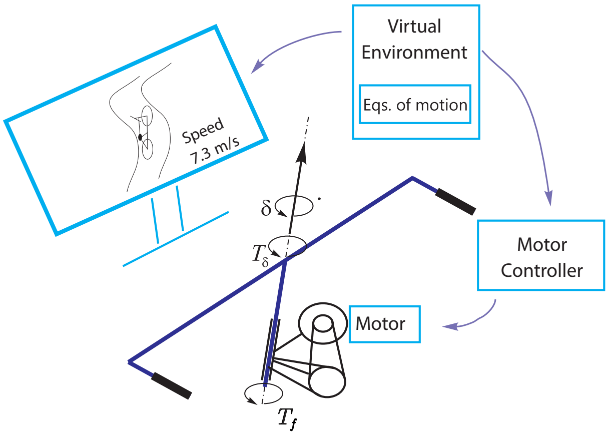

Figure 1. Scheme of bicycle simulator setup with haptic handlebar. T_f is the haptic feedback torque generated by the motor, T_δ is the torque applied by the user, δ is the degree of freedom of the system: the angle turned by the real handlebar

the actual handlebar state is coupled to the bicycle equations. Besides the handlebar inertia, two types of torques act on the steering axis when the haptic feed back is under operation: the input steer torque T_δ, exerted on the handlebar by the rider, and the haptic feedback torque T_f, whose mission is to transmit a realistic feeling of driving the bicycle (torque feedback from the equations of motion). In Figure 1 a simple sketch of the haptic system is shown. The dynamics of the (real) handlebar is governed by the following equation of motion,

$$I_\delta \ddot{\delta} = T_\delta + T_f, \tag{5}$$

with the mass moment of inertia I_δ of the complete haptic system (handlebar plus motor inertia). With the knowledge of the full state vector $(\varphi, \dot{\varphi}, \delta, \dot{\delta})$ and the roll angle acceleration $\ddot{\varphi}$, the haptic feedback torque T_f can be estimated from the steer angle equation (3) as,

$$T_f = -\left(M_{\delta\phi}\ddot{\phi} + C_{\delta\phi}\dot{\phi} + C_{\delta\delta}\dot{\delta} + K_{\delta\phi}\phi + K_{\delta\delta}\delta \right). \tag{6}$$

Including the real handlebar dynamics (5) into the linearized equations of motion (3) results into the equations of motion for the bicycle simulator,

$$\begin{bmatrix} M_{\phi\phi} & 0 \\ M_{\delta\phi} & I_\delta \end{bmatrix} \begin{bmatrix} \ddot{\phi} \\ \ddot{\delta} \end{bmatrix} + \begin{bmatrix} C_{\phi\phi} & C_{\phi\delta} \\ C_{\delta\phi} & C_{\delta\delta} \end{bmatrix} \begin{bmatrix} \dot{\phi} \\ \dot{\delta} \end{bmatrix} + \begin{bmatrix} K_{\phi\phi} & K_{\phi\delta} \\ K_{\delta\phi} & K_{\delta\delta} \end{bmatrix} \begin{bmatrix} \phi \\ \delta \end{bmatrix} = \begin{bmatrix} 0 \\ T_\delta \end{bmatrix}, \tag{7}$$

where the lack of contribution of the handlebar inertia to the roll angle equation may be noticed. This new system should show near to identical dynamical behaviour compared with the original linearized equations of motion.

4 Dynamics of the bicycle simulator

The equations of motion of the bicycle simulator (7) differ slightly from the original Whippel/Carvallo model (3). Therefore the bicycle simulator will behave differently from the original model. In order to make the simulator bicycle's behavior close to the benchmark equations, it is possible to adjust some coefficients in equation of motion for the haptic steer, the second equation in Eq. (7). In the first equation of (7) it is noticeable that the roll angle is not influenced by the inertia associated with the steering angle (there is a zero in that place). This approximation is acceptable considering the difference in the values of both inertias and the similarities in the eigenvalue plot. Conversely this approximation is not acceptable, i.e., the inertia of the bicycle connected with the generalized coordinate roll angle decisively affects the steering angle equation and thus it cannot be ruled out (for a bicycle with similar parameters). In the structure of a normal bicycle mass matrix, the term $M_{\phi\phi} \gg M_{\delta\delta}$ and there is a cross term $M_{\phi\delta} = M_{\delta\phi}$ that measures the importance of the coupling. If an eigenvalue analysis is performed to find out the features of the mass matrix in Eq. (3), the largest eigenvalue is related to the term $M_{\phi\phi}$ and the smallest to the $M_{\delta\delta}$ with certain influence of cross terms. The eigenvalues

Mass matrices	Eigenvalues λ_1	λ_2	Eigenvectors ϕ_1	ϕ_2
$\mathbf{M} = \begin{bmatrix} 80.8172 & 2.31941 \\ 2.31941 & 0.297841 \end{bmatrix}$	80.8840	0.231085	$\begin{bmatrix} -0.999586 \\ 0.028770 \end{bmatrix}$	$\begin{bmatrix} 0.028770 \\ 0.999586 \end{bmatrix}$
$\mathbf{M}_{\text{sim}} = \begin{bmatrix} 80.8172 & 0 \\ 2.31941 & \lambda_2 \end{bmatrix}$	80.8172	0.231085	$\begin{bmatrix} -0.999586 \\ 0.028770 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 1 \end{bmatrix}$

Table 1. Eigenvalues and eigenvectors for the original mass matrix $\mathbf{M}$ and the approximate bicycle simulator mass matrix $\mathbf{M}_{\text{sim}}$. Values used are from the benchmark bicycle [1].

define the relative importance of the inertia distribution of the system along principal directions (eigenvectors), which, in this case, come defined by the generalized coordinates ϕ and δ.

In order to preserve the relative importance of the eigenvectors and keep proper coupling between lean and steer, and taking advantage of the form of the mass matrix in Eq. (7), it is possible to choose a value for I_δ such that the approximated mass matrix' contribution to the bicycle equations is strikingly almost identical to the original one in the complete forward speed range. By setting I_δ identical to the smallest eigenvalue λ_2 of the original mass matrix the simulator mass matrix has eigenvalues $M_{\phi\phi}$ and λ_2. But far more important, it can be proven that the eigenvectors associated with the largest eigenvalue λ_1 are identical. It is this eigenvector that keeps a proper coupling between the lean and the steer motion for the largest eigenvalue. Moreover, these two largest eigenvalues do not differ very much form each other due to the dominance of the roll over the steer inertia. This is illustrated in Table 1. A comparison of the eigenvalues in a forward speed range of $0 < v < 10$ m/s between the original model and the bicycle simulator with the approximate mass matrix is shown in Figure 2. Note the stricking similarity in eigenvalues between the original model and the bicycle simulator for $I_\delta = \lambda_2$.

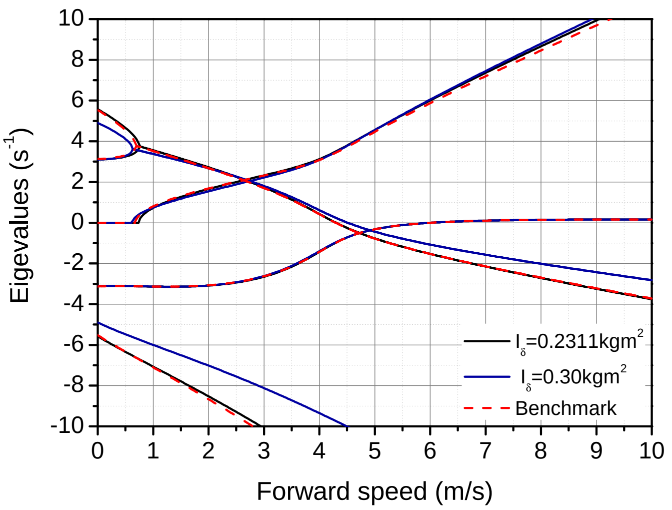

Figure 2. Eigenvalues of the benchmark bicycle in a forward speed range of $0 < v < 10$ m/s, dashed red lines, compared with the eigenvalues of the bicycle simulator with two different mass moments of inertia I_δ, an aproximate value of 0.3 kgm^2, solid blue lines, and the value of $I_\delta = \lambda_2 = 0.2311$ kgm^2, solid red lines. Note the striking similarity in eigenvalues between the benchmark and the simulator with $I_\delta = \lambda_2$.

5 Bicycle simulator set-up

The haptic handlebar is mounted on a stationary bicycle frame, see Figure 3. The rider/player will experience an almost complete riding sensation, i.e., he will be able to pedal and be seated while driving the handlebar. The haptic handlebar is mounted in a proper position, attached to the stationary bicycle. The flywheel and the training system can be used to shift

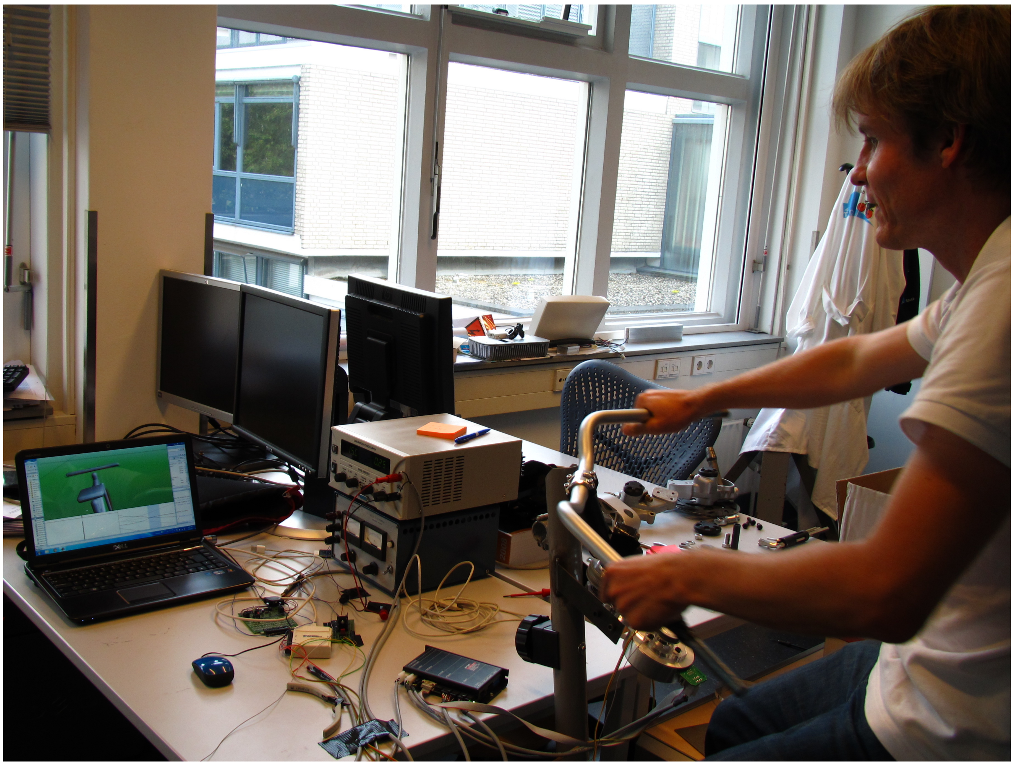

Figure 3. Experimental bicycle simulator setup with steering input device with haptic feedback and display with visual feedback.

the resistance. In case a proper velocity sensor is placed, this will allow to simulate different road conditions. The rider can watch a virtual reality environment on a display before him. The only important input missing in the haptic system are the vestibular ones, since the stationary bicycle does not lean as the integrated system do. However, visual input is available on the display. The mass moment of inertia of handlebar assembly with feedback motor has been tuned to match the requirements for the handlebar inertia ($I_\delta = 0.2311 kgm^2$).

The haptic handlebar attached to the frame is equipped with three different devices. Two of them collects information on the handlebar state: a potentiometer and an angular rate sensor provide information regarding the handlebar turning angle and its rate, respectively. This information is sent to data acquisition hardware, which is linked to computer model. The data stemming from the sensors can be filtered digitally by means of a low-pass filter. Note that, the filters can produce delays in the system that, due to the intended real-time characteristics of the simulator, can further jeopardize the stability of the system.

A block diagram of the setup is shown in Figure 4. At every integration step, the handlebar state is read and linked to the numerical integration of the roll (first) equation of (7). The rider exerts a torque on the handlebar affecting its state. This angular state is measured by sensors, digitalized and filtered. With this information we can integrate the roll angle equation, and prescribe a proper torque feedback according to (6). In a separate block de kinematics of the bicycle is calculated to obtain the position and orientation of the bicycle for visual display. The kinematics for the rear wheel contact point (x, y) and the rear frame heading ψ are governed by the differential equations [1],

$$\dot{x} = v\cos\psi, \quad \dot{y} = v\sin\psi, \quad \dot{\psi} = \frac{v\delta + c\dot{\delta}}{w}\cos\lambda, \tag{8}$$

which are integrated within the scheme together with the roll angle equation. The simple idea behind the coupling of this system is the following. The computer model samples the data measured on the handlebar at the same time step as the integrated variables, i.e., the roll angle and its rate. In this way we know the state of the whole system at this instant and we will output a proper signal to the motor controller so as for the rider to perceive realistic feedback on his/her upper limbs.

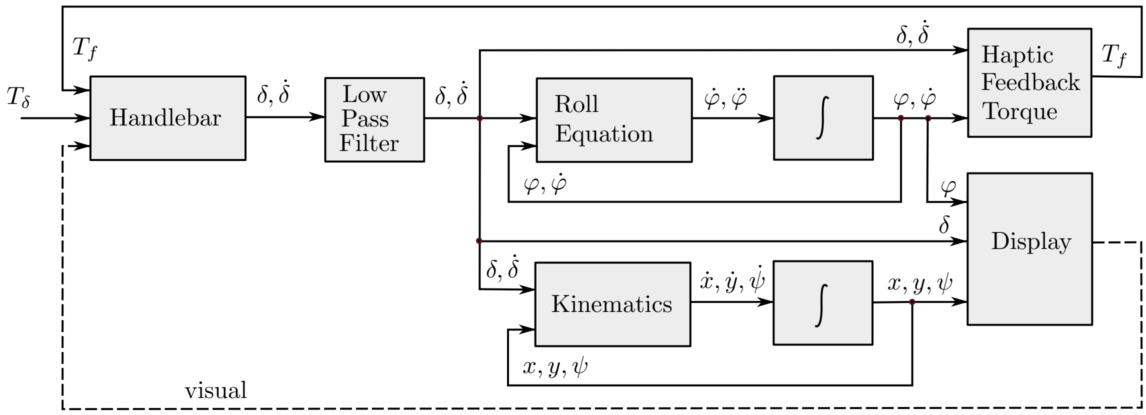

Figure 4. Block diagram of the bicycle simulator setup with the real handlebar dynamics, the measured and filtered steer angle δ and steer rate $\dot{\delta}$, the computer model roll equation and kinematics, the generated haptic feedback torque en a visual display. The hardware for this system is shown in Figure 3.

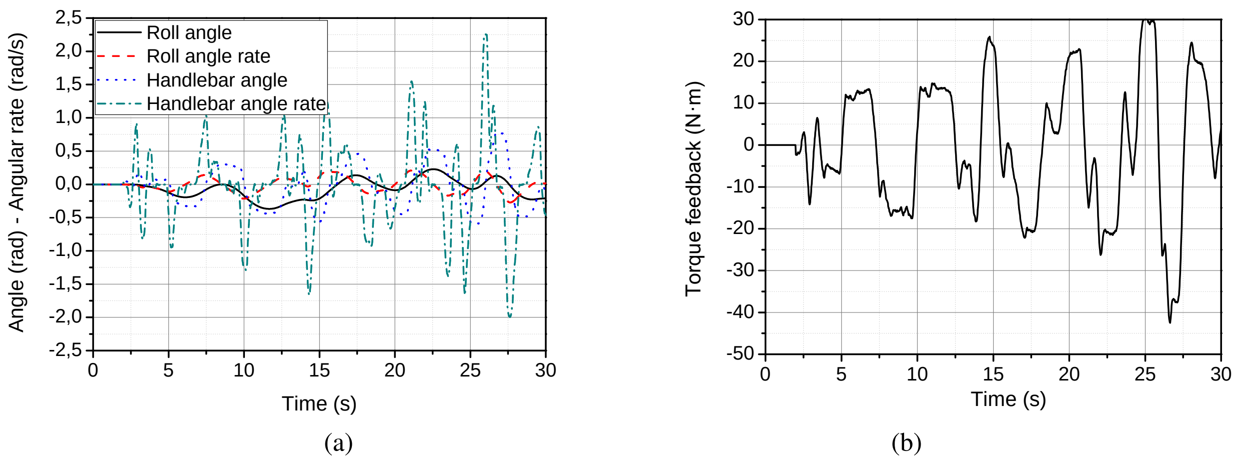

Figure 5. Measured results from an experimental run with the bicycle simulator at a simulated forward speed of 3.5 [m/s], at which the initially uncontrolled bicycle is laterally unstable. (a) Simulator (computer model) generated roll angle and roll rate of the rear frame of the bicycle together with the real handlebar steer angle and steer angle rate as a function of time, and (b) haptic feedback torque T_f generated by the computer model and fed back to the handlebars. The roll angle remains bounded, and clearly the rider is able to stabilize the lateral motions.

6 Results and conclusion

Some preliminary results from riding the bicycle simulator are shown in Figure 5. The bicycle is driven at a simulated forward speed of 3.5 [m/s], at which the initially uncontrolled bicycle is laterally unstable. Looking at the bounded values for the lean angle of the bicycle, it is evident that the rider is able to stabilize the initially unstable bicycle by steer torque input on the haptic handlebars. However, when the haptic feedback torque on the handlebar was turned off, the rider was unable to stabilize the lateral motions of the bicycle. This clearly demonstrates the need for haptic steer torque feedback in bicycling. Future work will be devoted to adding realistic pedal resistance, enhancement of the visual feedback and adding realistic sceneries.

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