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Bicycle Rider Control Modelling for Path Tracking

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Abstract: Rider models are employed to gain insight into bicycle rider steering behaviour and to improve characteristic properties of bicycles. In this paper, stability properties as well as basic dynamic characteristics of the passive (uncontrolled) bicycle–rider system and consequences on the rider control modelling are addressed. In particular, the unstable motion of the system at low velocities and bandwidth limitations caused by non-minimum phase dynamics are emphasized. To analyse the effectiveness of the steering torque and the lean torque as possible rider's inputs to control the dynamics of the bicycle, a controllability analysis of the bicycle–rider system has been performed. It turns out that lean torque input, in contrast to steering torque input, has marginal impact on the dynamics of the system. Finally, a bicycle rider control model considering human rider properties is presented, and its capabilities are demonstrated by performing a curve entering manoeuvre.

Keywords: Bicycle; Bicycle stability; Bicycle rider; Steering control; Controllability; Non-minimum phase systems

1. INTRODUCTION

The popularity of cycling, at least in urban areas, increased considerably in recent years. In the perception of the customer, the bicycle turned from a cheap means of transportation or a pure piece of sports equipment into a lifestyle accessoire. Furthermore, bicycles with additional electric propulsion ('e-bikes') increase comfort and meet the needs of elderly people by maintaining their mobility.

This popularity can also be seen in the growing number of scientific papers addressing the dynamics of the bicycle and the rider. An overview of papers on the dynamics of both motorcycles and bicycles is given by Limebeer and Sharp (2006), a comprehensive, recent review on bicycle dynamics and rider control literature is given by Schwab and Meijaard (2013). However, most of the research in rider control is dedicated to the rider of the motorcycle, see for instance the review by Popov et al. (2010), and more recent Massaro et al. (2012).

The need to understand the steering behaviour of the rider may result from an engineering requirement as well as from scientific interest. For vehicle dynamics simulations – with focus on the bicycle rather than on the rider – a 'virtual test rider' is needed to stabilize the motion of the bicycle and to track a demanded trajectory. From a more general point of view, insight into human steering behaviour of bicycles and conclusions thereof are desirable.

To distinguish driver/rider models from 'automatic driving controllers', at least some human key demands, for instance preview, prediction/anticipation, adaptation/learning or planning capabilities need to be mapped, see e.g. Plöchl and Edelmann (2007).

The rider influences the dynamics of the system on the one hand as controller by control inputs, such as steering torque applied to the handlebar, and on the other hand by adding dynamics to the system by rider movement relative to the bicycle, such as passive movement of the upper body w.r.t. the frame of the bicycle (Schwab and Meijaard (2013)). Thus, the dynamics of the bicycle cannot be investigated independently from the dynamics of the rider.

In this paper, characteristic results of (modal) controllability of the passive bicycle–rider model in Schwab et al. (2012) are compared to the model subsequently used for rider modelling, and a new rider control model is presented, that features basic properties of human bicycle riders and allows for stabilizing the motion of the bicycle and path-tracking tasks in simulation environments to analyse and optimise dynamical properties of bicycles.

In the following section, three passive bicycle–rider models tailored to specific applications by applying different depths of modelling are presented briefly. Stability properties of the uncontrolled system are investigated next. Then, specific dynamic properties of the bicycle and controllability aspects are discussed. Finally, the proposed rider control model is introduced and numerical results are presented.

2. BICYCLE AND RIDER DYNAMICS MODELLING

2.1 Bicycle–rider model

The representation of the dynamics of the bicycle–rider system applied in this paper for numerical simulation is basically the bicycle–rider model derived by Plöchl et al. (2012), see Figure 1. Besides the mass of the rider's upper torso m_r, the model consists of the masses of the mainframe m_m, including the lower part of the rider and

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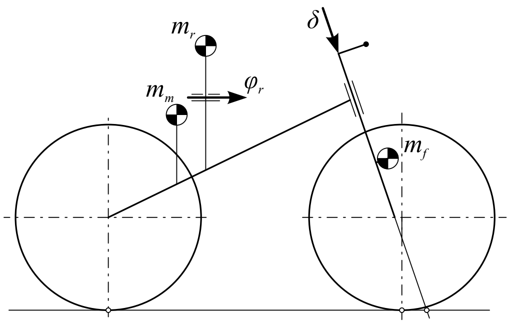

Fig. 1. Schematic representation of the bicycle–rider model.

the rear wheel, and of the front frame m_f, including the front wheel, and respective moments of inertia. The upper torso of the rider is represented by an inverted pendulum attached to the mainframe introducing a rotational degree of freedom φ_r supported by means of a linear spring–damper. The mainframe of the bicycle may lean with a roll angle φ and the front frame may rotate with respect to the mainframe with a steering angle δ about the steering axis. The longitudinal velocity v of the mainframe is assumed to be constant. As laterally slipping tyres including transient tyre dynamics are introduced, the mainframe may move laterally with velocity u and may rotate with yaw rate r. The active steering torque M_δ and lean torque $M_{\varphi r}$ are reacted on the rider's upper torso and the mainframe, respectively. For details on the modelling and parameters of the bicycle–rider system please refer to Plöchl et al. (2012).

2.2 'Internal bicycle model'

It is widely accepted in the field of human motor (muscle) control research that humans learn and store 'internal models' for use in motor control when interacting with the physical world, see for instance Keen and Cole (2010). Human have the ability to estimate future system behaviour by recalling relevant internal models from memory. These internal models are simplified representations of the dynamics of real physical systems.

In this work, the well-known basic Carvallo–Whipple or benchmark model, see e.g. Meijaard et al. (2007), has been selected to represent the internal vehicle model for bicycle rider control design. This bicycle model consists of four main rigid parts: the rear wheel, the mainframe which includes a rigidly attached rider, the front frame and the front wheel. Instead of laterally slipping tyres, ideal rolling of the tyres with no longitudinal and lateral slip at the wheel-to-ground contact is introduced. The mainframe is linked to the front frame at the steering head by a rotational joint that allows steering around an inclined steering axis. Thus, the degrees of freedom are the mainframe roll angle φ and the front frame steering angle δ; the longitudinal velocity v is considered constant.

Gathering the generalised coordinates in $\underline{q}_b = [\varphi, \delta]^\top$ and employing an external steering torque in $\underline{f}_b = [0, M_\delta]^\top$, the linearised equations of motion with respect to the upright, rectilinear motion of the benchmark bicycle are given as follows:

$$\mathbf{M_b}\ddot{\underline{q}}_b + (\mathbf{C_{0b}} + v\,\mathbf{C_{1b}})\,\dot{\underline{q}}_b + \left(\mathbf{K_{0b}} + v^2\,\mathbf{K_{2b}}\right)\underline{q}_b = \underline{f}_b \quad (1)$$

with mass matrix $\mathbf{M_b}$, damping matrices $\mathbf{C_{0b}}$ and $\mathbf{C_{1b}}$, and stiffness matrices $\mathbf{K_{0b}}$ and $\mathbf{K_{2b}}$. For more details on the benchmark model, please refer to Meijaard et al. (2007).

2.3 Extended benchmark model

To avoid the complexity of the more detailed model presented in Section 2.1 at investigating basic controllability aspects of the bicycle–rider system in later Section 5, the benchmark model is extended by an inverted pendulum linked to the mainframe of the bicycle to represent the lateral motion of the rider's upper torso, see Haudum (2012). Thus, an additional degree of freedom is added, $\underline{q}_e = [\varphi, \varphi_r, \delta]^\top$, as well as the additional rider lean torque in $\underline{f}_e = [M_{\varphi r}, M_\delta]^\top$:

$$\mathbf{M}\ddot{\underline{q}}_e + \underbrace{\left(\mathbf{C_{0e}} + v\,\mathbf{C_{1e}}\right)}_{\mathbf{C}}\dot{\underline{q}}_e + \underbrace{\left(\mathbf{K_{0e}} + v^2\,\mathbf{K_{2e}}\right)}_{\mathbf{K}}\underline{q}_e = \mathbf{E}\underline{f}_e \quad (2)$$

where $\mathbf{E} = [\underline{e}_{M_{\varphi r}}, \underline{e}_{M_\delta}]$, or in state-space representation,

$$\dot{\underline{x}} = \mathbf{A}\,\underline{x} + \mathbf{B}\,\underline{u} \quad (3)$$

with state vector $\underline{x} = [\varphi, \varphi_r, \delta, \dot{\varphi}, \dot{\varphi}_r, \dot{\delta}]^\top$, input vector $\underline{u} = [M_{\varphi r}, M_\delta]^\top$, system matrix $\mathbf{A}$ and input matrix $\mathbf{B} = [\underline{b}_{M_{\varphi r}}, \underline{b}_{M_\delta}]$.

3. STABILITY PROPERTIES OF THE UNCONTROLLED SYSTEM

To study characteristics of the dynamics of the benchmark model (1) in frequency domain, the matrix-valued polynomial

$$\mathbf{P}(s,u) = \mathbf{M_b}\,s^2 + (\mathbf{C_{0b}} + v\,\mathbf{C_{1b}})\,s + \left(\mathbf{K_{0b}} + v^2\,\mathbf{K_{2b}}\right) \quad (4)$$

is introduced, see Limebeer and Sharp (2006). The associated transfer functions are given by

$$\begin{bmatrix} P_{11}(s) & P_{12}(s,v) \\ P_{21}(s,v) & P_{22}(s,v) \end{bmatrix} \begin{bmatrix} \varphi(s) \\ \delta(s) \end{bmatrix} = \begin{bmatrix} 0 \\ M_\delta(s) \end{bmatrix} \quad (5)$$

where the roots of $\det \mathbf{P}(s,u) = 0$ represent the poles of the input–output transfer functions of the bicycle and the eigenvalues λ_k of the corresponding system matrix, respectively. Figure 2 shows the real and imaginary parts of the eigenvalues λ_k as a function of velocity v. Real parts of the eigenvalues need to be all negative for an asymptotic stable motion.

For the benchmark model, two well-known modes can be identified: the oscillatory weave mode and the monotonic capsize mode. While the first is unstable and has to be stabilised by the rider up to the weave velocity of about 5 m/s, the later turns unstable at velocities beyond circa 9 m/s. The eigenvalues λ_k referring to the stable monotonic caster mode are below -6 1/s and thus not depicted.

Further, the eigenvalues of the extended benchmark model (2) are plotted in Figure 2. Here, the additional asymptotically stable, oscillatory lean mode related to the rider's upper torso movement shows up. However, the introduction of the lean angle φ_r of the upper torso has only marginal influence on the unstable modes of the bicycle.

Besides both the extended and the benchmark model, the eigenvalues of the detailed passive bicycle–rider model