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Review article

Modelling human control of steering for the design of advanced driver assistance systems

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ABSTRACT

This paper reviews a set of scientific studies on how driver modelling may serve as the basis for designing advanced driving assistance systems. The work was aimed at explicitly representing the human visual and motor processes involved in the control of steering, and took into account current knowledge in the behavioural sciences. The nature and structure of the model, and its calibration using experimental data (identification), were addressed. Two design applications were considered: 1) estimating the driver state in various conditions of distraction and 2) building an automatic controller for haptic shared control of the steering wheel.

Contents

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1. Introduction

One of the key problems for the design of advanced driver assistance systems has been to predict the driver behaviour. The short-term prediction of the driver state, behaviour or intention could lead to the adaption of a future interaction. For example, the prediction of a driver's action on the vehicle's commands at a given point in time may give warning of an imminent critical situation. Conversely, an assessment that could be judged as critical on the basis of the observation of the vehicle-road system alone could be assessed as non-critical if it was predicted that the driver was already engaged in a correction maneuver. To address this question, we incorporated a driver model into the design process of driver assistance systems.

We used an interdisciplinary approach that consists of the design of human-machine systems on the basis of a model that explicitly represents the human perceptual, motor and cognitive processes involved in the task. The driver model used is termed cybernetic in accordance with A. N. Kolmogorov's definition of cybernetics: "the study of systems of any nature which are capable of receiving, storing and processing information so as to use it for control." Our goal was indeed to understand, study and reproduce the human way of driving. This model and its application focuses specifically on steering control, although the same approach could be adapted for other types of human-machine dynamic interaction. Hence, the inspiration for the model was current knowledge of the psychology of perception and the neurophysiology of motor systems. It represents perceptually valid sensory cues used by drivers and neurophysiologically valid sensorimotor systems. The rationale behind such an approach was first to build a theoretically grounded model that may be relevant both for control theory and for human behavioural science. From a more practical point of view, it was also a way to orient design choices as a function of specific hypotheses on the nature of perceptual and motor systems.

The first section of the paper will present the model structure and its psychophysiological foundations. It will also briefly address the question of its identification. Then, we will present how it has been used to detect and discriminate various states of driver distraction using the model prediction error, an analysis of the parameter variations or by considering distraction as an input additive disturbance. Finally, the application of the model in the design of a haptic shared control (HSC) automaton will be presented to show how model prediction can help to improve steering performance and to propose innovative indicators for evaluating the quality of human-machine cooperation. In the appendix, notations relating to models, control and indicators are given.

2. A cybernetic driver model of steering control

2.1. Structure and foundations of the model

Many attempts have been made to model driver steering behaviour as a lateral deviation regulator on the track. The approaches used have included optimal control, fuzzy logic, and neural networks (Plöchl & Edelmann, 2007). The validity of these models is most often limited to specific driving situations, in which the driver acts as a control organ, determining the actions required to follow the desired trajectory (Cacciabue, 2007). According to Mulder, Paassen, and Boer (2004), these models often ignore certain characteristics of human perception, which may affect control. Conversely, a cybernetic approach aims to represent the underlying psychological and physiological processes in accordance with current knowledge on sensorimotor control and cognition in humans. This is the approach we adopted in this study, whilst still maintaining our original aim to develop a simple enough model for use in the context of driving assistance design.

Fig. 1 presents the general architecture of the driver model. In order to steer the vehicle, the driver first needs to pick up relevant information from the visual scene (perception of the environment). Then, he must process this visual information to determine where he wants to drive. It has been proposed by Donges (1978) that the visual control of steering can be modelled as two complementary processes. One is fed by far visual information and allows for the anticipation of changes in the road curvature. The other is fed by near visual information and allows for the on-line correction of lateral position errors. This two-levels scheme has been validated by various experimental and modelling studies (Frissen & Mars, 2014; Land & Horwood, 1995; Salvucci & Gray, 2004). Visual information processing gives rise to a steering intention that needs to be converted by the neuromuscular systems into a force applied on the steering wheel, taking into account force and position feedback from the steering system.

The cybernetic model presented in Fig. 2 is consistent with the general architecture shown in Fig. 1. This model integrates and builds on previous work by our group (Sentouh, Chevrel, Mars, & Claveau, 2009) and that of others (Hoult & Cole, 2008; Salvucci & Gray, 2004). The reader can refer to Mars, Saleh, Chevrel, Claveau, and Lafay (2011) for details about the model theoretical background and to Saleh, Chevrel, Mars, Lafay, and Claveau (2011) for its implementation. The following section presents the essential points.

Visual anticipation is achieved by a simple proportional action on the angle at the tangent point, θ_{far} (Fig. 1). Land and Lee (1994) showed that drivers directed 65% of their glances toward the tangent point; thus, it has been proposed that looking at this point may be a way to read the road curvature at the sensorimotor level. Mars (2008) showed for instance that encouraging drivers to track any point that has the dynamics of the tangent point (but are not necessarily the tangent point itself) improves steering performance. However, it has also been debated that drivers may look at the future path (Wilkie, Kountouriotis, Merat, & Wann, 2010) or at the boundary of a safe trajectory envelope (Mars & Navarro, 2012), which often falls in the area of the tangent point. Whatever the case may be, we considered that using the tangent point as input to visual anticipation was a good enough approximation of visual information pickup in human drivers. In all cases, it more adequately represents information processing than solutions advocated in the past, which considered road geometry as a direct input to the driver model (Donges, 1978; Hess & Modjtahedzadeh, 1990).

It has been demonstrated that the visual compensation of lateral position errors can be achieved through peripheral vision of the road edge lines (Summala, Nieminen, & Punto, 1996). In line with a study by Salvucci and Gray (2004), we assumed that this can be represented as the compensation of the angular deviation of a near point (θ_{near}) perceived at a distance $\ell s = 5\,\mathrm{m}$ from the front

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