論文の内容の要旨

論文題目　Detection of Variations in the Neuromuscular State of a Driver via Mechanical Arm Admittance and Its Application to Haptic Steering Guidance
(腕の力学的アドミッタンスによるドライバの神経筋状態の変化の検知と力覚操舵支援への適用)

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本文

The originality of this work lies in the detection of impaired neuromuscular condition using driving-related variables, and the consideration of the neuromuscular condition of the driver when investigating the impact of application of haptic steering guidance on the neuromuscular condition of the driver. The estimation and understanding of the neuromuscular condition of the driver is critical since a misinterpretation can lead to substantial difference in the assistance that is needed to improve the condition of the driver. In the literature, studies that focus on haptic guidance investigates its effect on external metrics that result from neuromuscular condition, such as driving performances, reaction time, lane keeping, but do not investigate the neuromuscular condition itself. In this dissertation, the detection of an impaired neuromuscular condition, which is critical for the safety of the driver, is made possible using driving-related variables. This action is addressed by acquiring the neuromuscular condition of the driver and conclude on its variations. This estimation is made regarding to the reliability of the results, so that the estimation of the neuromuscular condition of the driver can be trusted to take a decision on the need of assistance. Moreover, it is demonstrated in this dissertation that the neuromuscular condition of the driver can be improved using short term haptic steering guidance application, which should pay special attention to the yaw rate variations of the vehicle in complex driving situations.

While driving, the main interaction of the driver with the control of the trajectory and the speed are made through the steering wheel and the gas or brake pedals. Thus, within the frame of driving control, the condition of the driver influences the accuracy of the actions of the drivers that aim to control the trajectory and the speed of the vehicle. The condition of the driver is related to the human neuromuscular condition, which refers to the unconscious response of the muscle to a perturbation regarding the stability of the dynamical joint. Playing the role of the regulator of the condition of the driver, the human neuromuscular system is a complex system of interactions that connects different physiological mechanisms, such as muscle activation, muscle co-contraction, body coordination, joint stabilization, body posture and balance. The movements of each limb of the human body are controlled by this system.

Because of neuromuscular fatigue, which can be caused by several factors, the control of the vehicle can be impacted negatively, and the safety of the driver can be compromised. The cause of a fatigued neuromuscular condition can be natural, when the body is exhausted after a long period without rest, for example, or irregular, when the driver is under the influence of alcohol, for example. For both natural and irregular influences, the reaction of the driver to unexpected event, such as obstacle apparition on the road, is largely shifted in time, or does not even happen. In most cases, this modification in the driver steering performance, gas pedal performance or brake performance leads to vehicle accidents. In order to remedy this issue, the neuromuscular condition of the driver must be monitored in real-time to detect any variations that may indicate a deprived condition and assist the driver in consequence.

Detecting the variations of the condition of the driver using driving-related variables such as the steering wheel angle or torque would benefit the ergonomics of the assistance system. Thus, it was demonstrated in previous studies that mechanical arm admittance permits to investigate the condition of the driver with the computation in the frequency domain of equations that include driving-related terms, or the computation in the frequency domain of equations that include bio-mechanical terms. This metric has been used in previous studies to estimate the condition of the driver in real-time car application and demonstrates the ability to assess accurately the variations of the condition of the driver. It is used in this dissertation to estimate the neuromuscular condition of the driver and its variations.

For investigating the impact of the variation of the condition of the driver on mechanical arm admittance, drivers presenting a deprived neuromuscular condition are asked to perform driving simulations, in which the estimation of mechanical arm admittance is performed. The amplitude of mechanical arm admittance of these trials is compared with trials performed with the same participants and in the same driving scenarios, at the exception that the participants presented a normal neuromuscular condition. This method permits to establish the influence of deprived conditions on mechanical arm admittance and quantify their effects. In this dissertation, the tested deprived conditions are drowsiness and distraction. It is demonstrated that these deprived conditions are increasing the amplitudes of mechanical arm admittance on different frequency ranges, which expresses a decrease of the arm stiffness and decreased capacities to react to steering perturbations. The occurrence of these decreases in amplitude of mechanical arm admittance occurred on different frequency ranges that varies depending on the type of impairment. Indeed, for a drowsy condition, which suggests both physical and mental impairment, the frequency range of mechanical arm admittance affected covers a larger frequency bandwidth compared to distraction, for which the impairment is only mental.

To remedy the negative impact of impaired neuromuscular condition, the application of haptic steering feedbacks on the steering wheel is proposed. Haptic steering guidance control applied to the steering wheel is a technology that provides steering feedbacks, which their amplitudes depends on geometric considerations of the trajectory of the vehicle compared with a desired trajectory. Usually, the amplitude of steering feedbacks is higher as the vehicle shift further from the desired trajectory. The geometric considerations of haptic steering guidance model are: the lateral position and velocity of the vehicle regarding the desired trajectory, and the yaw angle and rate difference regarding the yaw angle and rate of the desired trajectory. With haptic steering guidance control, drivers remain in the driving loop decision, and are constantly encouraged to perform accurate steering operations in order to maintain accurate lane-keeping performances.

To investigate the effect of haptic steering guidance control on the condition of the driver, the influence of the application of haptic steering guidance control on mechanical arm admittance is investigated. It is reviewed that the amplitude of mechanical arm admittance can be decreased by the application of haptic steering guidance, revealing an increase of the stiffness of the arm and an increased capacity to resist to steering perturbations. This statement denotes that the application of haptic steering feedbacks can influence the condition of the driver, enhancing the resistance to steering perturbations.

Moreover, optimal designs of haptic steering feedbacks, aiming at maximizing the decrease in amplitude of mechanical arm admittance, are investigated. It is found that haptic steering guidance design that focuses on the monitoring of the yaw rate of the vehicle, while maintaining a normal level of monitoring of the other variables, can optimize the decrease in amplitude of mechanical arm admittance. In this situation, the condition of drivers is influenced optimally, and the driving performances are improved.

Furthermore, it is reviewed that the benefits of application of haptic steering feedbacks to the steering wheel is restricted to specific conditions since drivers tend to present overreliance on the assistance while driving in complex driving situations. Whereas, they also present improved driving performances in term of lane-keeping and steering stability. Consequently, it is acceptable to apply haptic steering feedbacks for short periods of time in complex driving situations. In simple driving situations, haptic steering feedbacks dos not influence the condition of the driver because of the easiness of the steering tasks. As a result, the application of haptic steering guidance for short period of time seems beneficial to influence the condition of the driver who presents an impaired neuromuscular condition, aiming at improving the driver condition and driving performances.

To sum up the content of this dissertation, a driver can be influenced positively using short term steering haptic steering feedbacks, which pay a special attention to the monitoring of the yaw rate of the vehicle, in complex driving situations. Else, the haptic steering guidance does not have effect on the condition of the driver or can even induce overreliance on the assistance system.

Additionally, an impaired condition can be detected by observing increase patterns, depending on the frequency, of the amplitude of mechanical arm admittance that relate to a modification of the neuromuscular condition of the driver. Furthermore, the detection of impaired condition and the improvement of the neuromuscular condition of the driver can be made in real-time, which can fit real applications.