Hands On/Off Detection Based on EPS Sensors

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The state of the hands on the steering wheel is currently the most reliable indicator for evaluating the ability of the driver to control his/her vehicle. This has been confirmed by the last release of the UNECE regulation 79, which requires a vehicle to be equipped with lane keeping assist to automatically deactivate the function if the driver is not holding the steering wheel for longer than one minute. This paper presents a detection method which, instead of relying on dedicated sensors, uses sensors already available in most mass-produced EPS systems. They are used to compute a model-based estimation of the driver torque, which is subsequently processed using a threshold and a transition time window, to determine whether or not the driver is gripping the steering wheel.

Key Words: *Human machine interaction, Driver sensing, driver monitoring, Hands detection, Steering wheel, Automated driving, ADAS, LKA.*

1. Introduction

Advanced driver assistance systems (ADAS) are systems which help the driver to drive a vehicle. The system increases car and road safety when designed with appropriate human-machine interactions. The degree of automation of a vehicle has been classified by the Society of Automotive Engineers (SAE) from level zero, whereby the driver has full control over all functions, to level 5, whereby the vehicle is fully automated[1] (**Fig. 1**). Based on those classifications, it is only when a vehicle reaches the highest automation level that the human driver is no longer required for vehicle operation.

However, the current legislation does not allow vehicles to operate without the presence of a driver. For instance, the Vienna Convention on Road Traffic (1968)[2] states that "Every driver shall at all times be able to control his vehicle" and has been amended in March 2016[3, 4] so as to allow an automated system to drive the vehicle only if it can be switched off or overridden by the driver. More constraining is the UNECE regulation No. 79, paragraph 5.1 on steering equipment, which allows automated steering only for speeds up to 10 km/h[5]. A new revision has been released in November 2017 which extends the scope of the regulation from automated steering only at vehicle speeds below 10 km/h to include also driver assistance in keeping the vehicle within the chosen lane[6]. For vehicles with an automation level greater than 2, such limitations continue to apply.

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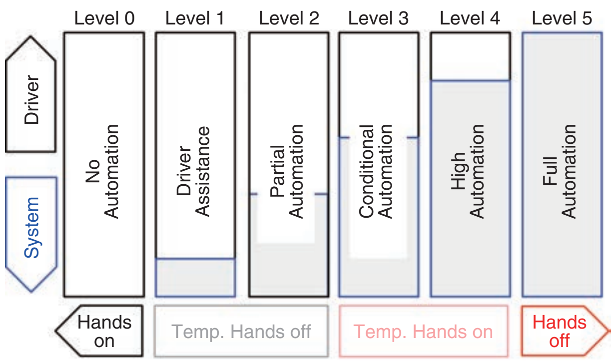


Fig. 1 Vehicle automation levels proposed by SAE

Hands-on the steering wheel is currently the most reliable indicator of the ability of a human driver to control their vehicle, at least in regards to lateral motion. Thus, its detection is likely to be required by these evolving regulations for the operation of automated vehicles below the maximum automation level, where control can be transferred to and from the driver.

This paper is structured as follows. Examples of applications for hand(s) detection are described in **Section 2**. **Section 3** presents the objectives and a proposal for specifications of the hands-on detection function. Different approaches to meet these specifications are presented and compared in **Section 4**, leading to the selection and further description of one of them: hands-on/off detection based on the driver torque. The results obtained are then presented in **Section 5**, followed by the conclusion in **Section 6**.

2. Application Examples of HOD

Two examples of scenarios describing different operating modes in automated vehicles are presented in this section for establishing the specification of the HOD function.

2. 1 Scenario 1: Hands-off Detection

The first situation in which HOD is already applied is the hands-off detection used together with the LKA function in automation level 2 vehicles. The goal is to make sure that the driver is always in control of the vehicle. Indeed, misuse of this function has already been identified as a relevant cause of accidents[10)].

2. 2 Scenario 2: Hands-on Detection

Vehicles that are highly automated might require the driver to take control, for example when traffic conditions are too complicated for the automated driving algorithms to handle. The transition from automated to manual driving mode should only be initiated after the driver's hands have been detected on the steering wheel (this is a necessary but, perhaps, insufficient condition). In critical situations, the control might have to be transferred urgently to the driver.

3. Specifications

Technically, the HOD function outputs a flag indicating that the driver's hands are, or are not, in contact with the steering wheel. The detection should be fast enough so as to provide sufficient time for decision-making within vehicle, passenger and traffic safety margin constraints. Its quality should be robust to parameter variations and within the full ranges and spectrums of all system inputs.

3. 1 Sensitivity

Physically, a firm grip is necessary so that sufficient friction force is generated at the interface between the hand and the steering wheel for transmitting the driver input.

In terms of sensitivity, the HOD function should enable distinguishing the hands-on from the hands-off state while satisfying the aforementioned definition of hand contact.

3. 2 Robustness

The detection of whether or not the driver's hands are on the steering wheel can be subject to two types of error:

- *False positives*: The system mistakenly outputs hands-on
- *False negatives*: The system mistakenly outputs hands-off

Because holding the steering wheel is a necessary condition to enable the transition from automated to manual driving (scenario 2), a false positive might lead to a state in which neither the driver nor the system are controlling the vehicle. False positives are safety-critical and consequently not tolerated. Conversely, when a false negative occurs, the driver is in fact holding the steering wheel and likely to control the vehicle. Although not safety-critical, false negatives may affect the driver's confidence in vehicle control. Consequently, false negatives are also not tolerated.

3. 3 Response Time

The time sequence for ensuring proper operation of LKA function when the driver is detected as unavailable has been prescribed in the UNECE R79[6)]. It is stated that if, after a period of no longer than 15 seconds, the driver is not holding the steering wheel, an optical warning signal shall be provided. Furthermore, if, after a period no longer than 30 seconds, the driver is not holding the steering wheel, an optical and acoustic warning shall be provided. Finally, the function shall be automatically deactivated at least 30 seconds after the acoustic warning signal has started. Under such legal framework, a response time of the hands-off detection should be less than 15 seconds.

A proposed time sequence in the case of a planned transition from AD to manual driving or take over request is illustrated in **Fig. 2**. In the case of such a planned traffic situation, a time period of up to 15 seconds is tolerated for unavailability of the driver. Above this time or in case of planned transition (with the driver being initially available), a period of up to 4 seconds is allotted for the transition to manual driving. If the driver does not satisfy all conditions for enabling this transition, a so-called minimum risk maneuver is initiated for ensuring safe immobilization of the vehicle.

The tolerated period of driver unavailability is not critical and justified as being a reasonable time for the driver to regain the condition of availability (e.g. seating on the driver seat, seat belt fastened, hands on the steering wheel, etc.). The transition time is provided to sense, decide and operate the transition. On a wet road surface and at the maximum speed of 130 km/h, it is bounded to 4 seconds for enabling override prior to initiating an automated emergency braking maneuver. In this case, the response time of the hands-on detection should be within the range of tenth of second so that enough time remains available for decision and operation of the transition.

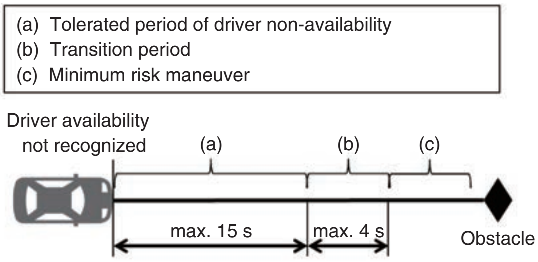


Fig. 2 Time sequence for planned transition from ADAS or AD to manual driving

4. Method

4. 1 Benchmark

Detecting the contact between the driver's hands and the steering wheel can be performed by adding dedicated sensors[7-9], typically of capacitive nature. The performance of a capacitive touch sensor is limited by their sensitivity. They have an inhomogeneous sensitivity distribution over an irregular surface. The tuning of the sensitivity is challenging as too low a setting requires hand contact over a wide surface (counted in the number of fingers), while too high a setting results in misdetection when the hand is close to the steering wheel but not in contact. Most of all, their implementation results in an increase of complexity and cost of both the product hardware and software. Conversely, a HOD function can be developed on the steering system with the benefits of relying on the available sensors only and implying minimum complexity and cost increase. While touch sensor based detection provides intuitive information: hand contact corresponds to the hands-on state, EPS torque based detection relates the hands-on state to the driver's steering action, which better reflects the actual state of the driver as being in control of the vehicle.

As an example, the method proposed in 11) and 12) is to apply an excitation torque to the steering wheel with the assist motor and to analyze whether the system response is closer to a hands-on or hands-off pattern. However, because it can be perceived as a deterioration of the steering feel, this method is not well accepted. Thus, a non-intrusive approach is preferred.

The proposed method is based on monitoring the torque applied to the steering wheel by the driver (driver torque). It is assumed that it is virtually impossible for the driver to hold the steering wheel without applying any measurable force for a certain period of time.

4. 2 Hands-on Detection Based on Driver Torque

This section discusses the method of detecting whether or not the driver's hands are on the steering wheel by monitoring driver torque.

4. 2. 1 Limitations of the Torsion Bar as an Approximation of the Driver Torque

The torsion bar is the only available sensor for measuring the driver torque in an EPS. Its resolution is sufficiently high, allowing the differentiation between a hands-on and hands-off situation in a stationary condition. The plots of **Fig. 3** validate the assumption that a driver cannot hold a steering wheel without applying force. Moreover, it could be interpreted that the driver is holding the steering wheel whenever the torsion bar signal exceeds a threshold value set above the noise of the hands-off signal.

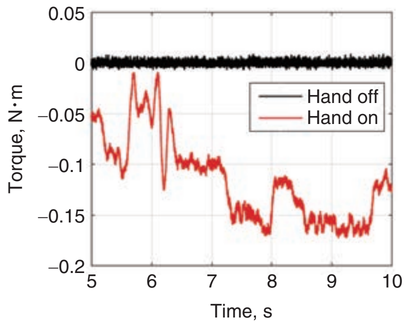


Fig. 3 Torsion bar signal in stationary condition (vehicle speed is null)

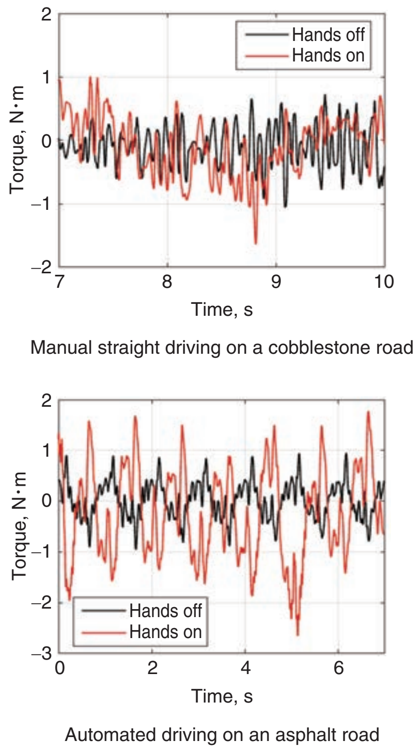


Fig. 4 Torsion bar signal during manual straight driving on a cobblestone road (top) and automated driving with a 1 Hz frequency 20 deg amplitude sinusoidal steering wheel angle command on a standard asphalt road (bottom). Constant vehicle speed of 20 km/h.

Because of its measurement principle, which is based on the relative angular displacement of the torsion bar extremities, the measured torque does not depend solely on the driver torque but also on the load applied to the other side of the sensor. This load is composed of any torque transferred from the tire-road contacts and the assist motor. **Figure 4** shows measurements of a vehicle evolving on a cobblestone road and in automated driving (smooth asphalt road). In those situations, the hands-off signal no longer remains around zero. The disturbances outweigh the driver torque, thus compromising the differentiation between hands-on and hands-off signals.

The dynamics of the steering wheel is used for explaining the limitation of using the torsion bar signal as an approximation of the driver torque. The Euler equation of the steering wheel is where J_{sw} and θ_{sw} are respectively the inertia and the angular displacement of the steering wheel, T_d the driver torque and T_{tb} the torsion bar torque.

$$J_{sw}\ddot{\theta}_{sw} = T_d - T_{tb} \quad (1)$$

The torsion bar torque T_{tb} is computed by measuring the relative angular displacement between the steering wheel and the lower end of the torsion bar θ_{tbl}. The stiffness of the torsion bar k_{tb} is considered only, while damping and friction effects are neglected.

$$T_{tb} = k_{tb}(\theta_{sw} - \theta_{tbl}) \quad (2)$$

Considering the dynamics of the steering wheel (1) in static condition, the angular acceleration of the steering wheel vanishes and, consequently, the torsion bar torque is equivalent to the driver torque.

$$T_{tb} = T_d \quad (3)$$

However, in a dynamic condition, the torsion bar torque is a function of the driver torque and the inertia effect of the steering wheel.

$$T_{tb} = T_d - J_{sw}\ddot{\theta}_{sw} \quad (4)$$

The relations (3) and (4) indicate that the assumption of considering the torsion bar torque equivalent to that of the driver is valid in static condition only. In dynamic condition, the inertia effect of the steering wheel is captured by the torsion bar, invalidating that assumption. Therefore, compensation of the inertia effect of the steering wheel is a prerequisite condition for robust driver torque estimation.

4. 2. 2 Estimation of the Driver Torque

A real time estimation of the driver torque is developed so as to obtain reliable information in all operating conditions. The so-called Driver Torque Estimator (DTE) is based on the extended state-space observer, a technique that has already been applied to steering systems[13]. The proposed DTE uses all available sensors of an EPS, namely the torsion bar (torque sensor) and the angle encoder of the assist motor, and will provide the base signal for the HOD function.

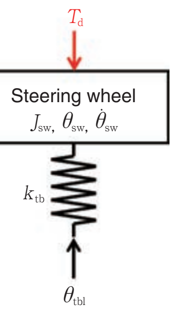


Fig. 5 Steering wheel and torsion bar model

The model chosen for the observer is presented in **Fig. 5**. It consists of a single inertia, that of the steering wheel, connected to the torsion bar, represented by a spring. The inputs of the system are the angle of the lower end of the torsion bar (known) and the driver torque (unknown), whereas its output is the torsion bar signal.

The state-space formulation of the Euler equation (1) of the steering wheel with the torsion bar torque (2) is written as follows:

$$\begin{cases} \dot{x} = Ax + B_1u_1 + B_2u_2 \\ y = Cx + Du_1 \end{cases} \quad (5)$$

where x is the state vector, u_1 the vector containing the known inputs, u_2 the vector containing the unknown input (driver torque), and y the output (torsion bar signal):

$$x = \begin{bmatrix} \theta_{sw} \\ \dot{\theta}_{sw} \end{bmatrix},\ u_1 = \theta_{tbl},\ u_2 = T_d,\ y = T_{tb} \quad (6)$$

The corresponding state, known input, unknown input, output and feedthrough matrices are respectively:

$$A = \begin{bmatrix} 0 & 1 \\ -\frac{k_{tb}}{J_{sw}} & 0 \end{bmatrix},\ B_1 = \begin{bmatrix} 0 \\ \frac{k_{tb}}{J_{sw}} \end{bmatrix},\ B_2 = \begin{bmatrix} 0 \\ \frac{1}{J_{sw}} \end{bmatrix} \quad (7)$$

In order to be estimated by a state observer, the unknown inputs vector u_2 is merged to the state vector x so as to generate an extended state vector x_e:

$$x_e = \begin{bmatrix} x \\ u_2 \end{bmatrix} = \begin{bmatrix} \theta_{sw} \\ \dot{\theta}_{sw} \\ T_d \end{bmatrix} \quad (8)$$

Thus, the state-space formulation of the system is extended as follows:

$$\begin{cases} \dot{x}_e = A_e x_e + B_e u_1 \\ y = C_e x_e + Du_1 \end{cases} \quad (9)$$

where the new lines and columns of the extended system matrices are filled with zeroes.

$$A_e = \begin{bmatrix} A & B_2 \\ 0_{1x2} & 0 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ -\dfrac{k_{tb}}{J_{sw}} & 0 & \dfrac{1}{J_{sw}} \\ 0 & 0 & 0 \end{bmatrix}$$

$$B_e = \begin{bmatrix} B_1 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ \dfrac{k_{tb}}{J_{sw}} \\ 0 \end{bmatrix} \quad (10)$$

$$C_e = [C \quad 0] = [k_{tb} \quad 0 \quad 0]$$

This was done under the assumption for observation that the unknown inputs have a slow rate of variations. The results of the DTE shown below prove that this assumption is valid.

The DTE is based on the observation of the states of the extended state-space (ESS) model. To this end, the observability condition of the ESS model (9) and (10) must be satisfied.

$$rank(O) = rank\left(\begin{bmatrix} C_e \\ C_e A_e \\ C_e A_e^2 \end{bmatrix}\right) = 3 \quad (11)$$

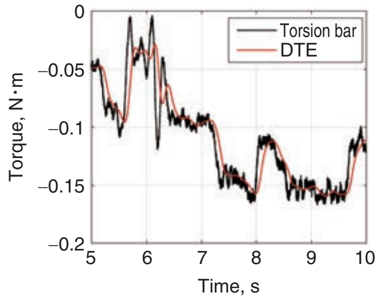
Because the rank of the observability matrix O is equivalent to the size of the state vector, a Luenberger state-observer can be designed. Applying this technique to an ESS model enables the estimation of the original system states as well as of the unknown input. This observer is written as follows:

$$\begin{cases} \dot{\hat{x}}_e = A_e \hat{x}_e + B_e u_1 + L(y - \hat{y}) \\ \hat{y} = C_e \hat{x}_e + Du_1 \end{cases} \quad (12)$$

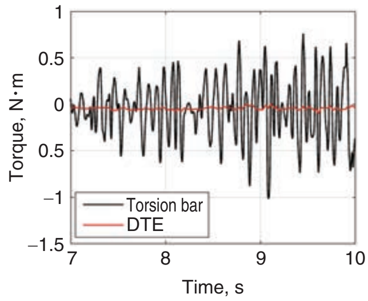
where the L matrix is computed by placing the poles of $A_e - LC_e$ in the left half of the complex plane, implying stability and convergence of the system. This means that the bandwidth of the observer can be tuned by placing the poles at the desired cut-off frequency. For a driver torque estimator, it is set to the bandwidth of the driver input.

Physically, this approach forces the model used in the observer to resemble plant behavior and extract the driver torque by compensating the inertia effect of the steering wheel.

The objective of the DTE is to reject the effect of the steering wheel inertia while achieving similar sensitivity to that of the torsion bar. To measure its performance, the DTE is compared to the torsion bar (**Fig. 6**). It is apparent that the DTE provides a sensitivity equivalent to that of the torsion bar for the purpose of measuring driver torque. A lag can be observed between the torsion bar and the DTE output. This is due to the bandwidth of the observer. On the other hand, it is significantly less sensitive to the inertia effect in a hands-off situation.



Hands-on in parking condition (vehicle speed is 0 km/h)



Hands-off situation while driving on a cobblestone road

Fig. 6 Comparison between the DTE output and the torsion bar signal for a hands-on situation in parking condition (top) and a hands-off situation while driving straight at 20 km/h on a cobblestone road (bottom).

4. 2. 3 Torque Threshold

Based on the estimation of the driver torque virtually independent from disturbances coming from the lower end of the torsion bar, a threshold has to be applied for distinguishing the two states of the hands. Because it has been specified that false positives are not tolerated, the threshold has to be set higher than any driver torque approximation error that the DTE is not able to compensate. Those errors are mainly due to hardware limitations such as sensor bias or internal friction.

4. 2. 4 Transition Time Window

Although it is nearly impossible for a driver to hold the steering wheel while applying a torque lower than the threshold for a certain period of time, the driver torque can remain momentarily under the threshold in the hands-on situation. An example is a torque sign change, where the HOD function should output a constant hands-on state. In order to prevent such false negatives, output change of the HOD cannot rely solely on the amplitude of the driver torque but also on the time spent under that threshold. This is performed by starting a timer whenever the signal passes under the threshold. If the timer reaches the end of a set time window, the hands state switches to hands-off. The length of this time window has been set at the value for which no false negatives are observed. It is to be noted that the transition from hands-off to hands-on does not require such an algorithm because the threshold has been set so that it is never crossed by the driver torque estimation in the hands-off situation.

4. 3 Summary of the HOD

The resulting structure of the HOD function is summarized in **Fig. 7**. It is based on the driver torque estimator, which outputs a signal virtually insensitive to the inertia effect of the steering wheel. A torque threshold ensures distinction between the hands-on and hands-off states, thus defines the sensitivity of the system. Finally, a time window prevents the HOD output from mistakenly switching to hands-off during the short instants when the driver torque can happen to be below threshold in a hands-on situation. The time response of the system is defined by the DTE time constant and, additionally for the hands-on to hands-off transition, the time window. A virtually fully reliable detection is possible as it depends on the representability of the data available for tuning.

Fig. 7 Structure of the HOD function

5. Results

To evaluate the performances of the HOD, its output is compared to the actual state of the driver's hands while the steering wheel is being periodically held and released. The driver grip complies with the aforementioned definition of hands-on. Two situations are presented: a manual driving situation on a cobblestone road, corresponding to scenario 1, (**Fig. 8**) and an automated driving on an asphalt surface (**Fig. 9**) for scenario 2. The torsion bar and the DTE outputs are presented in the upper portion of the figures.

It can be seen that the DTE is sufficiently sensitive to detect the contact of the driver's hands on the steering wheel while being unaffected by other disturbances so that its output remains below threshold in a hands-off situation. Thus, the HOD successfully detects every instant when the driver's hands are on or off the steering wheel without yielding false positives or false negatives.

Furthermore, the response time of the system also meets the specifications: a tenth of a second for hands-on detection and less than two seconds (due to the time window) for hands-off detection.

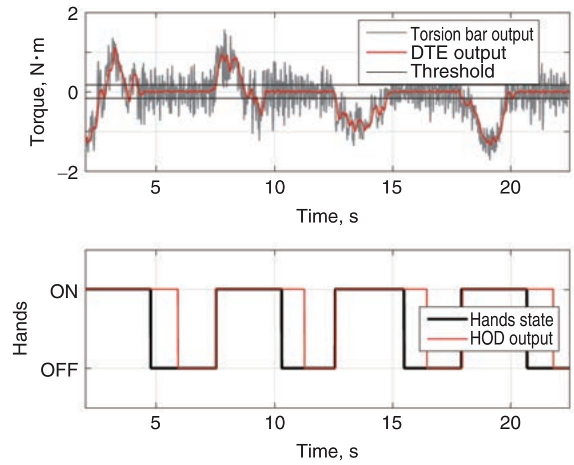


Fig. 8 HOD performance in straight manual driving on a cobblestone road with the driver periodically holding and releasing the steering wheel. Constant vehicle speed of 20 km/h.

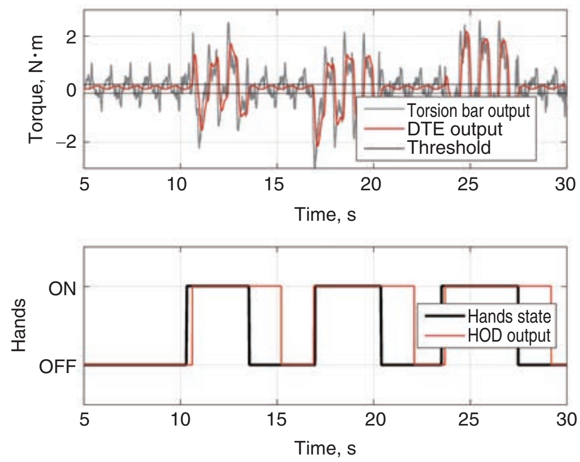


Fig. 9 HOD performance in automated driving on asphalt with the steering wheel following a 1 Hz and 20 deg sinusoidal commands and with the driver periodically holding and releasing the steering wheel. Constant vehicle speed of 20 km/h.

6. Conclusion

The detection of the hands on the steering wheel presented in this paper is an add-on software function that can be implemented in the ECU of an electric power steering. It relies only on the available sensors of most mass-produced EPS and requires no hardware modification. The detection is sensitive, fast, and reliable. Tuning is straightforward with three physically meaningful parameters: the cut-off frequency of the observer, the torque threshold and the transition time window.

The proposed model-based approach does not rely on any loose assumption. The problem is elegantly formulated resulting in a simple linear observer that generates minimum computing load.

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