Design of an Adaptive Feedback Based Steering Wheel

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Abstract. This paper aims at describing the architectural model of an adaptive force-feedback for a By Wire steering wheel system. This solution uses a steering wheel to replicate the reactive torque law which allows the driver to complete a precise driving scenario or a task with the higher performances. Then, the steering wheel adapts the reactive torque to the driving scenario. Since the design of this system considers the driver performances, it is called Ergonomic Steer-By-Wire. Now a prototype version of the ESBW is connected on a professional driving simulator and several tests are going to be conducted in order to tune the system components. Adapting the force feedback to the driving scenario could be a solution for improving driver's safety and vehicle control.

Keywords: HMI, steer-by-wire, driver performances.

1 Introduction: Human Factors Studies in Steering Systems

The aim of the study is to create a reconfigurable force-feedback system for a by-wire steering wheel (Zheng, 2005) which allows the driver to complete a precise driving scenario with the higher performances. The force feedback manager which takes care of the human performance is called Ergonomic Steer-By-Wire (ESBW). The field of "X-by-wire" systems have been investigated and used in other fields, such as the avionic and is now being largely explored within the automotive area. This study selected a SBW control due to a technical reason: in a SBW no mechanical junctions between the front wheels and the steering control are necessary, and hence the steering dynamic can be completely reconfigurable. It is in fact electronically commanded and can be completely controlled by a software.

In literature each force feedback law reproduced by the steering wheel can be classified into two categories:

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1. proportional to the steering angle;
2. based on vehicle dynamics.

The force feedbacks from the first group are also called “spring-based” since the reactive torque increases with the steering angle. These are the most common laws replicated on driving simulators since they emulate the transmission on the steering of the auto-alignment of the front tires (Gillespie, 1992). The cons of this group is that they represent an approximation of the control of the vehicle and thus the driver is not able to feel the real dynamic of the car.

The force feedbacks of the second group are based on the vehicle dynamic. That is, the reactive torque is replicated as a function of several vehicle parameters, like the speed, the yaw rate, yaw angle, lateral acceleration, sideslip. The pros of this solution is that the driver can feel how the vehicle moves on the steering; however, this force feedback based solution is more difficult to implement.

The idea of a reconfigurable force feedback for a steering wheel comes from an analysis of the literature on human factors studies in driving control. This analysis focused on the relationship between the driving performance of the driver, his or her interaction with the steering wheel and the driving environment.

For instance, previous works stated that in certain road paths a specific force feedback law loaded on the steering wheel gives higher performances than with other force feedback. It was found that drivers driving on a curvy road or rural path feel that they have an especially high vehicle stability control when a reactive torque based on lateral acceleration or yaw rate is loaded on the steering wheel (Kimura, 2005). The same results where not confirmed in the highway where drivers where seen to prefer a spring-based reactive torque (Mourant, 2002).

In these works, the driver performances were assessed using several driver behavior indexes, in particular self reporting measures (Nasa Tlx, RSME, etc. - Aide, 2004; Östlund, 2004) driving performance measures (standard deviation of lateral position, steering entropy, speed variation, etc. - Östlund, 2004) and physiological measures (hart rate, eye movements, etc. - Aide, 2004). Then, it was possible to state that a certain force feedback is better than another one in a specific context of use: for example, a comparison between a spring-loaded and a force feedback based on vehicle dynamics in a rural road driving scenario (including curves of 100, 200 and 300 radii) was presented in (Mourant, 2002). The aim of the study was to understand which was force feedback that gave the driver the better maneuverability and control of the vehicle. The preference for a vehicle’s dynamic force feedback was confirmed by analyzing a) the drivers’ performance through several measures like the mean lane position of the vehicle on the road and b) self-reporting measures, that is, a questionnaire on the feeling of the two force feedbacks.

A list of the best force feedback solutions for each driving scenario was created; the list represents a basis for the development of a preliminary work on the so-called ESBW. Starting from this list, the ESBW aims at reproducing the best force feedback for a specific scenario.

In order to test whether the ESBW is comfortable and safe for the end user, several tests on a driving simulator will be completed.

2 Selection of the Best Force-Feedback Solutions

The Ergonomic Steer By Wire aims at improving the driver performances during driving in specific scenarios. The study of the ESBW is conducted on a driving simulator in a laboratory on Mechatronics named MECTRON and placed in Reggio Emilia (North of Italy)[1] and it is currently developed and tested on a driving simulator.

The first step for the development of the ESBW was a study conducted in 2006 by the MECTRON laboratory regarding the literature on human factors studies in vehicle steering control. The study focused on identifying the best force feedback solutions reproduced by different driving control systems (e.g. standard steering wheel, steer-by-wire, joysticks and so on) in specific driving conditions. The driver performances were analyzed by monitoring specific physiological, performance-based or self reporting measures as described above. The result of the research was presented in *tables of correspondence* between the most common driving environments and the best force feedback law sourced by the literature. An example of the table applied to the case of a rural road scenario is depicted below.

Table 1. Correspondence between driving scenarios and best force-feedback solution

Scenario	*Study*	*Best Force Feedback solution*	*Measures of performance*
Rural road	Pei–shih, 2004	1) at low speeds the feedback force is dependent on yaw-rate. 2) at intermediate to high speeds the feedback-force is obtained from lateral acceleration	Available in Huang, 2004
Rural road	Toffin, 2003	Force feedback proportional to steering angle: 1) Linear with an angular coefficient of 1,5 [N x m/rad] 2) Linear with an angular coefficient of 2,5 [N x m/rad] 3) Parabolic with saturation at 4 [N x m/rad].	Standard Deviation (SD) of lateral acceleration, steering angle and lateral deviation.

The information filled in the table was used to select the best performing force feedback solution which has to be implemented on the ESBW in a specific driving environment. Since for each driving scenario more than one force feedback law are available (e.g. for rural road, 5 laws are listed – see Table 1), it was decided to limit the number of force feedback laws to one for each scenario.

To do that, a further selection of the force feedbacks listed in the *tables of correspondence* like Table 1 has to be carried out. Then, several tests are going to be completed on a fixed driving simulator; the aim of the tests is to assess what force feedback law allows the driver to increase his/her performance in a specific driving

[1] Mectron (www.mectron.org) is a research Laboratory of the Hi-Mech technological district placed in the north of Italy (http://www.hi-mech.it).

scenario. A description of the test is provided at the end of the document. In order to test each force feedback solution the architectural model of the ESBW was developed. In the next paragraph, the design concept of the system is described.

3 Architectural Model of the ESBW

The design concept of the ESBW can be summarized in the figure below. In this figure, the high level functionalities of the system are depicted.

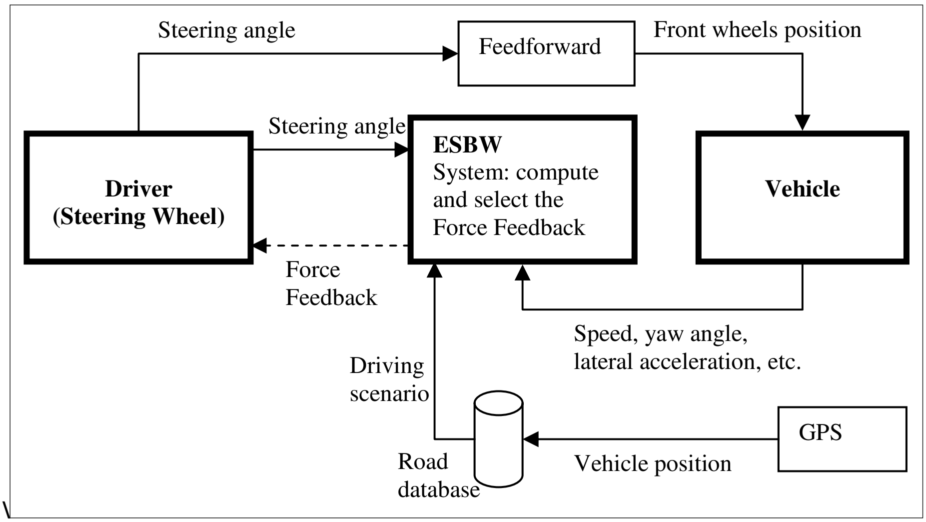

Fig. 1. Design concept of the ESBW system

Fig. 1 shows the main components of the ESBW. The solid lines entering the ESBW subsystem represent the input of the systems, while the dotted lines are the output. To compute the reactive torque for giving feedback to the driver, the ESBW needs three main components: the driver, the vehicle and a vehicle's position system (e.g. a GPS).

As mentioned before, the force feedback laws may be classified into two categories: steering angle based and vehicle's dynamic based. Since the position of the steering wheel is required for the first group, the ESBW has to source this parameter from the driver steering; after that it may compute the required force feedback and replicate it on the steering wheel.

As for the second category, several vehicle dynamic's parameters (e.g. speed, yaw angle, lateral acceleration, etc.) are required to compute the force feedback; the ESBW has to source them from the vehicle.

The signals corresponding to the steering angle and the vehicle's dynamic can be directly sourced from the vehicle's CAN (Controller Area Network).

Finally, the ESBW has to select the force feedback solution to be replicated on the steering wheel in a specific scenario. In order to do that, it is necessary to know the position of the vehicle and to identify the current type of scenario. Since a the GPS system is able to track the position of the vehicle, a road database connected to the GPS would be able to identify the driving scenario (e.g. city road, highway, rural road, mountain road, etc.) and communicate it to the ESBW. This kind of information is now available in modern car navigation system.

Focusing on the internal logic of the ESBW, a schema of the system is depicted in the following figure.

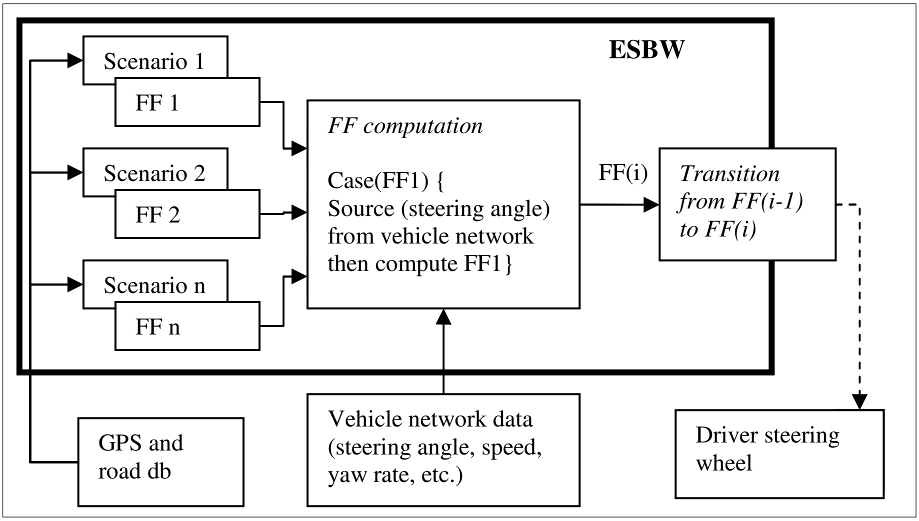

Fig. 2. Internal logic of the ESBW

As shown in Fig. 2, the internal logic of the ESBW is composed by three main components:

1. the scenario and force feedback laws database (database subsystem);
2. the computation of the force feedback laws (computation subsystem);
3. the communication of the force feedback to the driver (communication subsystem).

Point 1 of the list represents the result of the collection of the best force feedback laws for each driving scenario sourced by the literature. This information is filled into a database which links the best force feedback to the related scenario. Point 2 is the subsystem related to the calculation of the force feedback which has to be replicated on the steering wheel: data related to what force feedback the systems has to compute is sourced by the database (point 1) and the parameters needed for the computation (e.g. steering angle, yaw rate, etc.) are sourced by the vehicle CAN network. Finally, point 3 describes the subsystem related to the transmission of the force feedback to the driver (i.e. steering wheel); since the ESBW aims at loading a different force feedback law for each driving scenario, it is necessary to transmit the new force feedback which has to be reproduced in the most driver-comfortable way. In fact, an abrupt modification of the vehicle handling behavior may lead to risks for the driver's safety. Moreover, a bad design of the transition from a force feedback law to the next one, may cause an out-of-the-loop syndrome (Endsley, 1995; Billings, 1991; Wickens, 1992), compromising the effectiveness of the automation introduced by the ESBW as the drivers have the impression to be excluded from the controlling task. An example of how the ESBW works is shown in the following use case (Table 2).

Table 2. Example of a Use Case for the ESBW

Pre-condition
GPS and road database communicate to the ESBW the road the vehicle is moving: at time t(i-1) the vehicle is moving in an highway road. A certain force feedback (FF(i-1)) is reproduced on the steering wheel .
Use case story
1. At time t(i) the vehicle is moving on a Rural road. 2. The new scenario is revealed by the GPS, then it is communicated to the database subsystem of the ESBW. 3. The database selects the new force feedback to be reproduced on the steering wheel (i.e. FF(i)) and communicates it to the computation subsystem. 4. The subsystem sources the data needed to compute the FF(i) from the vehicle network, then FF(i) is executed. The values (output) of the FF(i) are transmitted to the communication subsystem. 5. The subsystem generates the transition from the previous force feedback loaded on the steering wheel, FF(i-1), to the new one, FF(i), in a specific time interval and following a precise transition rule (e.g. a smooth transition can be provided).
Post-conditions
After the time interval of the transition phase, the correct force feedback is reproduced on the steering wheel.

4 Interface of the ESBW with a Driving Simulator

The logic of the ESBW is now under development and tuning in a simulated environment. Using Matlab Simulink/Stateflow[2] a prototype of the final system was created and it is going to be tested on a driving simulator. The design of the prototype's high-level logic is described in Fig. 1 and Fig. 2.

The simulator used for HMI studies on the ESBW is composed by:

- a car cabin of a real vehicle (i.e. the vehicle driven by the subjects of a test) equipped with pedals (brake, clutch and accelerator), gear box, hand-brake and a steering wheel;
- a projection system which shows the driver the driving scenario, the vehicle interaction with the driving environment and traffic into a front screen;
- an Ethernet network which allows the communication among the car cabin, the simulated scenario and the data recording system.

The most interesting component is the steering wheel; it is an Active Steering Wheel System (ASWS)[3] which emulates the behavior of a Steer-by-Wire (SBW)

[2] www.mathworks.com
[3] http://www.conekt.net

system. Like an electronic SBW, the dynamic of the ASWS can be completely software controlled.

Since the simulator can be connected to Matlab Simulink/Stateflow by using specific APIs (Application Program Interface), a connection between the ESBW prototype system and the simulator was created. According to Fig. 1, GPS data and Road database data are completely sourced from the simulator environment by connecting the database subsystem of the ESBW to a simulated GPS receiver; thus, the vehicle position and the type of the road are available. Moreover, the set of data needed for the computation subsystem of the ESBW (i.e. vehicle dynamic and steering wheel data) are sourced from a simulated electronic unit able to source CAN messages from the vehicle's network which is simulated by the simulator's Ethernet. Finally, the ESBW is able to transmit to the driver the specific force feedback computed in the Matlab workspace by modifying the dynamic of the force feedback actuator installed on the ASWS; thus, the driver will feel the reactive torque reproduced by the ESBW.

Now all the components of the ESBW prototype have to be tuned in order to create a system which is comfortable and safe for the driver. In particular, the following step are going to be completed:

- *Tuning of the database subsystem*: for each driving scenario it was decided to reproduce only one force feedback on the steering wheel in order to reduce the complexity of the system and the number of transitions from a force feedback law to another one.
- *Tuning of the computation subsystem*: after the tuning of the database subsystem, the computation of all the selected force feedback has to be reproduced in a single subsystem.
- *Tuning of the communication subsystem*: in order avoid possible risk situations due to the transition from a force feedback law to the next one replicated on the steering wheel, different transition solutions have to be assessed on the drivers during several tests on the simulator.

Now the prototype of the ESBW developed for the test on the simulator is configured for the tuning of the database subsystem. Then, it is able to:

- receive from the simulated GPS and Road database the scenario where the vehicle is moving;
- associate the scenario to a specific force feedback law;
- compute the selected force feedback law;
- replicate the force feedback on the steering wheel without transitions.

The selection of the best force feedback solution for the tuning of the database subsystem is made through the assessment of the driver behavior and performances during driving. A description of the test is depicted in the next paragraph.

5 Experimental Test: Tuning of the ESBW

A test aiming at tuning the database subsystem of the ESBW was prepared; the results of the test will be the selection of only one force feedback law for a specific driving scenario. The results will be available in the middle of 2007.

Six different force feedback laws were selected from the *table of correspondences* before mentioned. These force feedbacks have been tested and reported in literature both in highway road and rural road environment. Three force feedbacks are classified as proportional to steering angle and they are sourced by Toffin, 2003 and Godthelp, 1985; the others are based on vehicle dynamics and they are sourced by Segawa, 2001, Pei –shih 2004 and Kimura, 2005.

In order to compare the force feedbacks and select the best one for a specific scenario, the same environment as in literature were created, that is, a highway road and a rural road. Furthermore, a city road was created in order to test each force feedback solution and verify whether one of them gives better performance in this scenario.

The test will be carried out on 54 young subjects, aged between 20 and 30. Each driver will be asked to drive for 40 minutes in the three mentioned scenarios. During driving, the drivers are asked to perform a primary task, that is, to drive in the lane, make several lane changes in precise coordinates of the road and to drive in traffic. For each driving task, the ESBW transmits only a force feedback law to the steering wheel, then it is configured to work like a traditional steering system. While driving, a set of behavioral measures of the drivers will be collected. A part of the selected measures was the same of those used in the literature works from where the force feedbacks laws were sourced, in particular:

- driver performance measures: Standard Deviation (SD) of steering angle, SD of lateral acceleration, SD of yaw angle, deviation from the lateral lane;
- self reporting measures: RSME (Rating Scale Mental Effort - Zijlstra & Van Doorn, 1985), four level sensory evaluation scale (Nakano 2005).

In this way, it will be possible to compare the results of this test with the literature. Furthermore, other driver behavioral data are planned to be recorded in particular:

- driver performance measures: HFC (High Frequency component of steering angle), SE (Steering Entropy), TLC (Time to Lane Crossing);
- self reporting measures: Nasa – TLX, DQS (Driving Quality Scale);
- Physiological measures: heart rate inter-bit-intervals, heart rate variability, skin conductance variation.

All the mentioned measures are listed and described in (Östlund, 2004) and (Aide, 2004). Other tests on the tuning of the ESBW subsystem database are going to be completed on the driving simulator: in the end, one force feedback law for each driving scenario will be provided. As for the tuning of the computation subsystem, several functionality tests will be provided on the ESBW's prototype in the Matlab Simulink/Stateflow workspace. Finally, the tuning of the communication subsystem will be carried out on the drivers by testing several transition solutions.

6 Conclusions and Future Steps

The main aim of the ESBW is to allow the driver to improve his or her performance during driving by providing a different force feedback law for each driving scenario.

One of the further steps of the activity carried out on ESBW aims at exploring how it can be used to provide warnings and information to the user for ADAS (Advanced

Driver Assistance Systems) functions (e.g. Lane Departure Warning, Curve Warning, Lane Keeping Systems – Aide, 2004), putting the level of driver support, the optimal feedbacks and the driving scenario in close relationship. For example, an appropriate torque to suggest the driver the right maneuvers (aborting the overtaking, or keeping the vehicle inside the lane) could be provided. Important results can be achieved in this area, as a practical example of use of the ESBW system as informative channel.

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