DEVELOPMENT OF AN INTEGRATED UPPER LIMB VEHICLE CONTROL: HAPTIC DRIVE-BY-WIRE DEVICE

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ABSTRACT

The main goal of the project presented in this paper is to study the driveability of motor vehicles using only upper extremities, with real-time haptic feedback in a drive-by-wire (DbW) hand-operated control. After a thorough revision of existing solutions in car adaptations for disabled people, aeronautic controls and concept cars, a prototype device has been developed. This prototype manages steering, throttle, brake, and gears of the vehicle with only hand and arm movements. Its design has been defined considering the opinion and expectations of people with lower extremity disabilities, who are potential beneficiaries of that concept, as well as ergonomic criteria, in order to achieve a simple, smart and user-friendly device, attractive and easy to control even by inexperienced users. Three main targets have been aimed to in the development of this device: ergonomic design, realistic and effective force feedback, and to follow an inclusive approach. A compact, smart-looking device has been designed, oriented to a technologic, futuristic image.

Keywords: drive-by-wire, haptic feedback, ergonomics

1. INTRODUCTION

There are different driving forces leading to new concepts of vehicle control. From the technological point of view, electronic and “by-wire” solutions can remove many mechanical constraints of conventional devices, like steering wheels, pedals, gearshifts, etc., and this encourages innovative designs to improve usability and driver’s experience. Moreover, automobiles are nowadays a basic commodity, so there are social needs that must be met by modern vehicles.

In countries like Spain, UK or the US, 10-15% of people are affected by some disability; the most important types of disability are lower extremity impairments and other problems related to lack of mobility, which affect from 3% to 5% of population (1-3). They constitute an important share of potential drivers, who need to adapt their vehicles to make them accessible. Unfortunately, currently available adaptations often have limited functionality, or their design is severely subordinated to assembly needs, since they are built independently from the vehicle they must be installed on.

This paper presents a drive-by-wire (DbW) hand-operated control, designed under the following premises:
• It must be easily controlled by people with partial or total impairment of their lower limbs, and have a small demand of upper limb actions.

• The styling must follow an inclusive approach, so that it does not look as an orthopaedic adaptation for disabled people, but an enhanced control that provides an improved driving experience for new vehicles.

• Ergonomics and usability are the basis of the design, to ensure that it is a simple, smart and user-friendly device, attractive and easy to control even by inexperienced users.

The following sections describe the design criteria and methodology in detail, and the results of a first prototype that has been integrated in a driving simulator for user trials.

2. METHODS

2.1. Analysis of Current Adaptations

In the first place, we evaluated 11 different existing alternatives to conventional driving by steering wheel and pedals, in order to determine the main advantages and limitations of the state-of-the-art. These alternatives are chiefly joystick-based devices (levers and mini-steering wheels installed on the driver’s side, and connected to the vehicle electronic system), adaptations to the steering wheel (supplementary handles and rings, mechanically connected to the pedals to accelerate and brake with the hands), and adaptations to the pedals in order to steer the vehicle with foot movements (designed for upper-limb impaired drivers).

The criterion followed to evaluate these solutions was to assess their aptness to different types of disabilities, and usability issues. While both joystick-based devices and steering wheel adaptations were apt for people with total impairment of lower limbs and limited functionality of upper limbs, only joysticks could include all the actions needed to drive, without additional complements.

On the other hand, the reduced range of movement of joysticks controlled by position (where the amount of acceleration, deceleration or the steering angle is directly related to the angle of the joystick with respect to its neutral position) was an additional issue for people whose disability could be related to coordination or spasticity problems. This problem is amplified by the possible coupling of forward/backward and side movements of the joysticks, which are used for clearly distinct actions (throttle/brake and steering, respectively). Such coupling is contrary to the independence rule of axiomatic design recommendations (4), and may pose an important safety issue. To prevent this problem, some designs aim at decoupling the frontal and lateral movements, making one of them translational and the other one rotational (5), or using one lever for each action, which must be operated with different hands.

2.2. User Panel

As users’ needs had to be the basis of the development, in the early design stages we conducted a user panel, with the participation of 10 customary (5 female and 5 male) with lower limb disabilities, who drove regularly in vehicles with adapted controls. The participants were experienced in using both mechanical and electronic adaptations, and all used an automatic gear shift. In the discussion session they were asked for the type of adaptations they had used, their advantages and limitations, and possible improvements in a future hand-operated control. The conclusions of this session were used to define the design requirements of the DbW device.
2.3. Basic Concept

After evaluating the advantages and limitations of the state-of-the-art, and the needs and preferences of users, the concept chosen for the driving device was an electronically operated joystick, that could be seamlessly integrated in the vehicle, and keep all its functionalities (mechanical adaptations usually limit the functionality of other devices, like the airbag).

One of the most important problems to solve with this type of device was the need of decoupling steering and throttle/brake actions, while ensuring a smart design, and a simple and intuitive usage. Peter’s and Östlund’s joystick (5) solved this problem by using different types of hand movements for each action. However, it didn’t solve a conflict that exists with respect to the suitable direction to accelerate and brake: a usual practice, following ergonomic recommendations and standards for machine tools (6-7) is to accelerate by pushing forward, and brake by pulling backwards. However, during braking inertia may push the driver forward, and make him underbrake, so some commercial solutions implement the opposite criterion (8-9).

In order to circumvent this conflict, we chose a motorbike handle-like design, where accelerating is performed by rolling the handle backwards and decelerating by the opposite movement. Moreover, this choice allows an enhanced decoupling of throttle/brake vs. steering, by connecting each action to a different part of the driver’s upper limb: throttle and brake is performed by rotating the wrist, and steering by a lateral movement of the forearm (a rotation of the humerus, see figure 1).

![Figure 1: Joint movements associated to throttle/brake (left) and steering (right).](image)

2.4. Functional Requirements

The following requirements were defined for the driving device:

- Using “by-wire” technology, that allows a smooth transmission of efforts and haptic feedback.
- Force-feedback for all actions.
- Lever for emergency brake, different from smooth braking, to allow a precise control of acceleration, and also reduce speed instantaneously with a moderate effort.
- Allowing cruise control, to reduce hand tension due to continuous need of accelerating.
- Steering ratio dependent on vehicle speed, to keep a constant sideward acceleration due to steering.
- Low-pass filtering of steering and acceleration signals, to prevent accidental steering and allow smoother driving.
- Maximum angle of the handle from neutral position: 60°.
- Throttle/brake maximum angle: 45°.
• Including auxiliary functions in the device: automatic gearshift, parking brake, turn signals, and possible other functions.

• Possibility of using two controls (one at each side of the driver), with complementary auxiliary functions (e.g. left/right turn signals), and synchronized throttle/brake and steering functions. This would reduce the effort needed, enhance driver’s control, and improve the device’s robustness and flexibility. However, it should be combined with a folding system to allow the driver to enter and exit from the vehicle.

2.4. Ergonomic Requirements

The detail design of the device was done according to ergonomic criteria regarding European and American anthropometry (10), ranges of movement of the hand (11-12), perception and fine movement capabilities (13), and force thresholds applied to manipulation of tools and controls (10,13-14), as well as on the basis of European standards about machinery controls (15-16).

The dimensions of the device were defined to fit hand measures ranging from female 5th percentile to male 95th percentile. Its position in the vehicle’s cabin was defined in RAMSIS, to ensure a comfortable reach for a Class A vehicle (H-point height = 266 mm, torso angle = 25°, see figure 2).

![Figure 2: Position of the device for male 95th percentile (top) and female 5th percentile (bottom)](image)

The throttle control was rotated 20° forwards in the coronal plane, and in its neutral position the tip was tilted 20° upwards, to fit the neutral posture of the hand and arm. Its length and diameter, as well as the size and position of the emergency brake lever and auxiliary buttons (cruise control, automatic shift, parking, and others), were defined according to the following criteria:

• Ensuring an appropriate grasp.

• Small deviation from neutral position of hand, wrist and fingers.

• Keep all controls within reach of objective population.

• Preventing accidental pushing of buttons.
3. RESULTS

The final concept is materialized in a prototype controlled by computer, whose final outer appearance is shown in figure 3. The device differs from other joystick-based concepts, in the design and placement of the controls. Unlike in conventional joysticks, the different functions are operated by a wider set of upper limb actions (not only arm deviation and button pressing, but also wrist rotation, and hand grip), which make it closer to a motorbike handle. Nevertheless, its design aims at a “smarter” and more futuristic appearance, with more functions, implemented in buttons that can be manipulated with the thumb while holding grasp on the throttle bar, and a smooth and elegant outer look, that can be integrated in new concept cars.

![Figure 3: Final design of the DbW concept.](image)

Two DC motors control the rotation resistance to the throttle/brake and steering manoeuvres. The former is an axial rolling of the throttle bar, and the latter is a rocking movement with a low centre of rotation (see figure 4). In both cases, a encoder measures the angle turned by the driver, while the DC motors produce a torque in the opposite direction, to simulate the mechanical resistance of the road and the vehicle motor, in order to provide an adequate force feedback to the driver.

![Figure 4: Mechanical skeleton of the DbW prototype.](image)

These opposing torques are calculated on the basis of the intensity of driver’s action, vehicle speed, gear, and power. The force counteracted by the driver in his rolling the throttle/brake bar produces a proportional amount of acceleration or deceleration. This imitates the response of pedals, and minimizes driver’s workload when using a joystick (5). Speed control is further enhanced by the cruise control function: when the desired speed is reached, the driver can hold it by pressing a button at the end of the throttle bar with the thumb, until some action
(rolling the throttle bar forwards, pressing the brake lever, or changing the gear) cancels it. Thus, the driver can relax the wrist while keeping in total control of the vehicle.

Regarding the response to steering, the angular range of the DbW device is small with respect to conventional steering wheels, so the function that relates the lateral rotation of the control and the angle of wheels must have a high gain; but this is detrimental to precision, and may cause involuntary oversteering. So we applied a nonlinear gain function, which is recommended to address this problem (17). We have also used a speed progressive steering scaling (5), where the steering ratio decreases with the driving speed.

The integration of the DbW device with other electronic control systems, like ABS, ASR, or ESP, may provide enhanced force feedback in case of irregular response of the wheels. This kind of active feedback improves the control of the vehicle (18).

The DbW prototype is connected to a PC station through a dSPACE card, and a ControlDesk application that integrated the DbW haptic algorithms and the vehicle model of the rFactor driving simulator (figure 5). This integration has been successfully tested in dirt road and highway scenarios, with informal evaluations of driveability, compared with driving those scenarios with usual simulator controls (steering wheel and pedals).

![Figure 5: Driving simulation with the DbW prototype.](image)

4. CONCLUSIONS AND FUTURE WORK

The DbW device that has been described is a new concept for ergonomic, smart and inclusive driving. By concentrating all the necessary functions to drive the vehicle in a hand-operated device, this is an opportunity to advance in the inclusive design of vehicles. People with lower limb disabilities are one of the clearest beneficiaries of such a concept, but it does not add important restrictions to upper limb capabilities. The dimensions, ranges of movement and forces of the device have been chosen to meet ergonomic criteria, and the cruise control function may allow to relax the wrist effort and driver’s workload in long travels.

Moreover, the design of the device has been driven away from orthopaedic solutions. A compact, smart-looking device has been designed, oriented to a technologic, futuristic image. The algorithms for force definition allow drivers to feel realistic, smooth and unequivocal driving feedback experience, as assessed in informal tests with a prototype integrated in a PC station with a driving simulator.

An important amount of future work is still to be done, to transform this concept into a reality in the automobile market, but the grounds are already set. The electronic control of all the vehicle functions allows to replace the conventional controls of vehicles with this (or other) devices, and the most important OEM are already going for concept cars with this kind of innovative solutions without steering wheel (19-22). The tests with driving simulators prove
that such solutions are feasible, and may allow an acceptable control of the vehicle, besides important advantages with respect to traditional solutions.

The following step to advance in the development of DbW is to validate it with their potential users, by means of an experimental design in more integral, immersive and realistic environments. In this process, we expect to find further opportunities to enhance its usability and functional characteristics, and improve the state-of-the-art for the future driving and mobility of all the people.

ACKNOWLEDGEMENTS

This work has been supported by the project MARTA, led by FICOSA INTERNATIONAL S.A. and Funded by the Centro para el Desarrollo Tecnológico Industrial (CDTI) for the 3rd CENIT Programme, as a part of the INGENIO 2010 Programme of the Spanish Government.

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