Origo Steering Wheel: Improving Tactile Feedback for Steering Wheel IVIS Interaction using Embedded Haptic Wave Guides and Constructive Wave Interference

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Automotive industry is evolving through “*Electrification*”, “*Autonomous Driving Systems*”, and “*Ride Sharing*”, and all three *vectors of change* are taking place in the same timeframe. One of the key challenges during this transition will be to present critical information collected through additional onboard systems, to the driver and passengers, enhancing multimodal in-vehicle interaction. In this research authors suggest creating embedded tactile-feedback zones on the steering wheel itself, which can be used to relay haptic signals to the driver with little to no visual demand. Using “Haptic Mediation” techniques such as 3D-printed Embedded Haptic Waveguides (EHWs) and Constructive Wave Interference (CWI), the authors were able to provide reliable tactile feedback in normal driving environments. Signal analysis shows that EHWs and CWI can reduce haptic signal distortion and attenuation in noisy environments and during user testing, this technique yielded better driving performance and required lower cognitive load while completing common IVIS tasks.

CCS CONCEPTS **Human-centered computing → Human Computer Interaction (HCI) → Interactive Systems and Tools**

Additional Keywords and Phrases: Steering wheel tactile feedback, Constructive Wave Interference, Embedded Haptics Waveguides, Origo Wheel, autonomous vehicles, user study.

1 INTRODUCTION

The automotive industry is transitioning towards a cleaner, smarter, and more connected future. However, this multigenerational shift brings new challenges for the drivers. The added information from semi-autonomous driving systems [1], smart road infrastructure [2], additional sensors [3] and computational systems [4] within the vehicle and personalized secondary communication tasks, can all become overwhelming for the driver. Furthermore, studies show [5] that some drivers prefer to interact with their own personal devices (phones, tablets etc.) as these may provide unrestricted social media access compared to the in-vehicle interaction systems. This means that drivers of current generation vehicles need to process and react more than ever before to information from several sources, which makes driving a much more demanding task. On top of this, the transition towards various levels of vehicle autonomy (SAE 1-3) in current hybrid and electric vehicles that introduce additional complexity, can severely increase the amount of information that the driver needs to assimilate, process, and react to, while driving [6]. Even the possibility of these radical changes themselves challenge certain drivers with confusion and alienation, because almost everything drivers have been currently used to, may change.

2 STEERING WHEEL INTERACTION

Most of the current information is presented audio-visually [1] on the center stack or instrument cluster. This means that the driver needs to shift their attention from the primary driving task to interact with input elements for common tasks (e.g., turning on the windscreen wipers in a Tesla Model 3/Y) which can be dangerous [7, 8]. Although efforts have been made to include physical buttons and switches (i.e., on steering wheels) for specific tasks, dedicated buttons are limited in design by their functionality and often require some visual attention from the central stack. Multifunction sensor pads on the steering wheel, as suggested by Honda's Steering wheel concept (*CES2020*), can be very useful for inputting gestures and selections especially for unconventional electrification or automation related tasks. However, their lack of tactile output makes them difficult to use without diverting visual attention from the road. Ideally, dynamic touch surfaces [9] on the steering wheel that can be used as both haptic input and output can complement visual and auditory information provided from the onboard displays / HUDs within the vehicle. However, providing reliable tactile output, without signal attenuation and integration on the steering wheel in a moving vehicle has been quite challenging [10, 11, 12, 30] due to 1) limitation in actuation components, 2) mediation of signals to the point of contact, and 3) mitigating environmental noise. In the present work the focus is on solving these challenges by using 3D-printed Embedded Haptic Waveguides (EHWs) [13, 14, 15] within the steering wheel to mediate the tactile feedback from the actuator to the point of contact. Moreover, utilizing the novel concept of Constructive Wave Interference (CWI) [16, 17], where two oppositely placed actuators are used to create virtual excitors at the point of contact through modulating their output signals, authors developed a customized 3D-printed steering wheel that can provide reliable tactile feedback in a variety of haptically noisy environments for a range of tactile signals.

3 SYSTEM AND EXPERIMENT DESIGN

The developed Steering Wheel was an extension of the work carried out during the MIVI Project on the "Origo Steering Wheel" (OSW), hence the outer design of the steering wheel was consistent with the publicly available version shared in the 2021 German Design Awards [18]. This paper details the haptic interaction aspect of the Origo Steering Wheel (OSW).

3.1 Steering Wheel Design

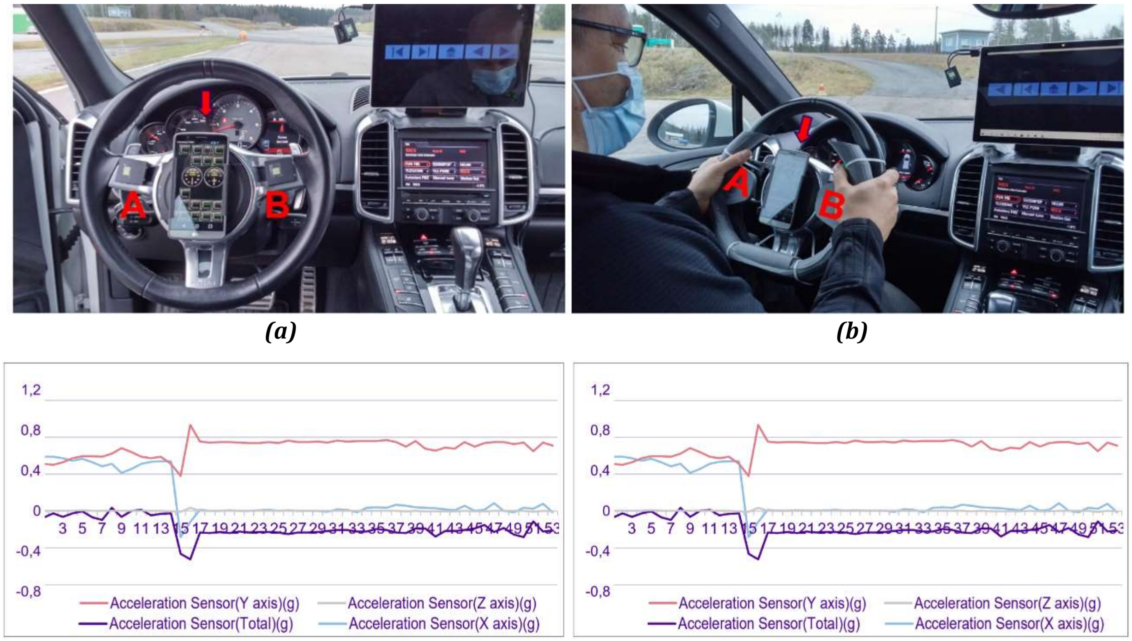
The 3D-printed Steering wheel with EHWs was developed by shafts and indentations consistent with [19]. As waveguides are essentially a medium where the wave propagation is bounded in two directions of space and free in the third one [20, 21], the 3D-printed design utilized ABS plastic material (100% fill rate) as the mediation channel and empty space around it act as the isolating area (Fig. 1). Using this design, we created waveguides that mediated the actuation signals from the central area to the entire periphery. Two centrally mounted Lofelt L5 actuators (Fig. 1) were used to create virtual excitation throughout the periphery of the steering wheel using Constructive Wave Interference (CWI).

Figure 1: Designing the Embedded Haptic Waveguides for the Origo Steering Wheel. Top left: the haptic channels resonating from the wings of the wheel; Top right: the width and spacing between the channels at 1:1 ratio for 60Hz actuation resonance; Bottom left: the Origo wheel structure and actuator placement for optimum CWI localization; Bottom right: the second version of the Origo wheel from the German Design Awards.

Constructive Wave Interference or CWI, is when two or more physical actuators, generate complimentary signals which coalesce into a single output on the surface of interaction, localized, as a virtual exciter. Implementing CWI on the wheel using L5 actuators meant that virtual excitors could be calibrated for any part of the periphery of the steering wheel by modulating the amplitude and frequency of the two centrally mounted actuators [17]. This ensured dynamically adjustable actuation depending on driver's point(s) of contact, making the feedback more efficient and localized using capacitive sensors. However, for this study we focused creating virtual exciters through CWI to the point just below the wings of the Origo wheel at points A and B (Fig.1).

3.2 Experiment Design

To test the usability and viability of the OSW with EHWs we compared it to a conventional steering wheel with identical actuation components mounted at the wings of the wheel (Fig. 2) of a Porsche Cayenne turbo 2016. The OSW was attached on top of the original steering wheel of the vehicle to ensure the control of the vehicle was not hampered. Both steering wheels were connected to a center stack consisting of Microsoft Surface Tablet with Bluetooth transceivers and an amplifier for the Lofelt L5 actuators mounted on top of the dashboard next to the embedded IVIS display (Fig. 2). Modulated 60Hz, 150ms actuation signal generated while driving 60Km/h on *Nokian Tyres Testing Track* (NTTT) was sampled at the bottom center of the grip area (A & B) to identify actuation output variations between the two wheels. Pilot testing of the setup showed that the 60Hz modulated signal provided the most efficient virtual actuation at the bottom center of the steering wheel combining CWI and EHWs design of the Origo Steering Wheel (OSW). Testing showed that the recorded signal (used for confirmation feedback) on average was 18-24% stronger on the OSW compared to the original steering wheel.



(a) ***(b)***

(c) ***(d)***

Figure 2: Top left ***(a)***: the design and placement of actuation component (Lofelt L5) on the Original Steering Wheel (OSW) of the Porsche; Top right ***(b)***: design and attachment of the 3D-printed Origo wheel; Bottom left ***(c)***: the actuation recorded

at the central point of the OSW; Bottom right ***(d)***: actuation recorded on the Origo wheel at 60km/h on the *Nokian Tyres Testing Track*, straight.

To evaluate this setup, we recruited 8 professional *NTTT* drivers to drive a 460m straight section of the track while performing 2 common IVIS tasks, an onscreen keyboard *"Text Entry"* and a dynamic *"Menu Selection"*. The recruitment of professional drivers on the NTTT ensured that experimental software and hardware did not create any safety concerns for the participants, as their jobs entailed testing various hardware and software system in challenging road conditions. The two tasks (Text entry and Menu selection) were performed 3 times each, one for each run condition (visual only, Origo Wheel and Original Wheel) by all 8 participants. The *"Text Entry"* task involved entering randomly generated 8 characters with onscreen keyboard. The *"Menu Task"* required the users to follow 6 randomly generated sequences of actions [22] on a dynamically changing music control bar (with *Reverse, Forward, Home, Next, Previous* buttons). Both tasks (order balanced) were carried out while the drivers drove the straight section of the track at a constant 60Km/h, which essentially gave them 28 seconds to complete each task. The drivers were asked to prioritize their primary task of driving and try to complete the secondary task as soon and accurately as possible. As discussed earlier both tasks were carried out in three conditions: 1) OSW, 2) the original wheel with attached actuators, and 3) visual only feedback from the system. Driving performance measures (Steering Wheel Reversal Rate (SRR), Standard Deviation Lane Position (SDLP), and Speed variation) and secondary task performance measures (Task Completion Time (TCTs), Errors, Task Incompletes (TICs), Screen contact time, and Touch-point accuracy) [Fig.3] were recorded and logged for analysis. Additionally, a 6-point NASA TLX version was used to track drivers' cognitive load and frustration. Each participant drove one lap of the track without secondary tasks to record their baseline driving behavior.

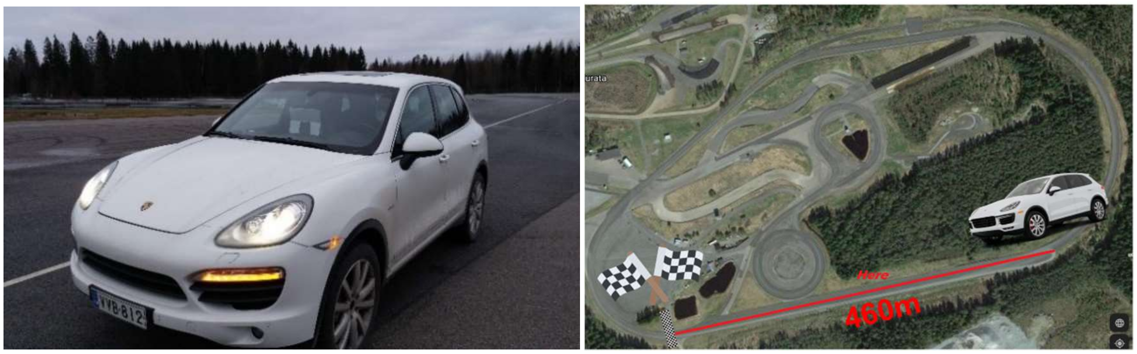
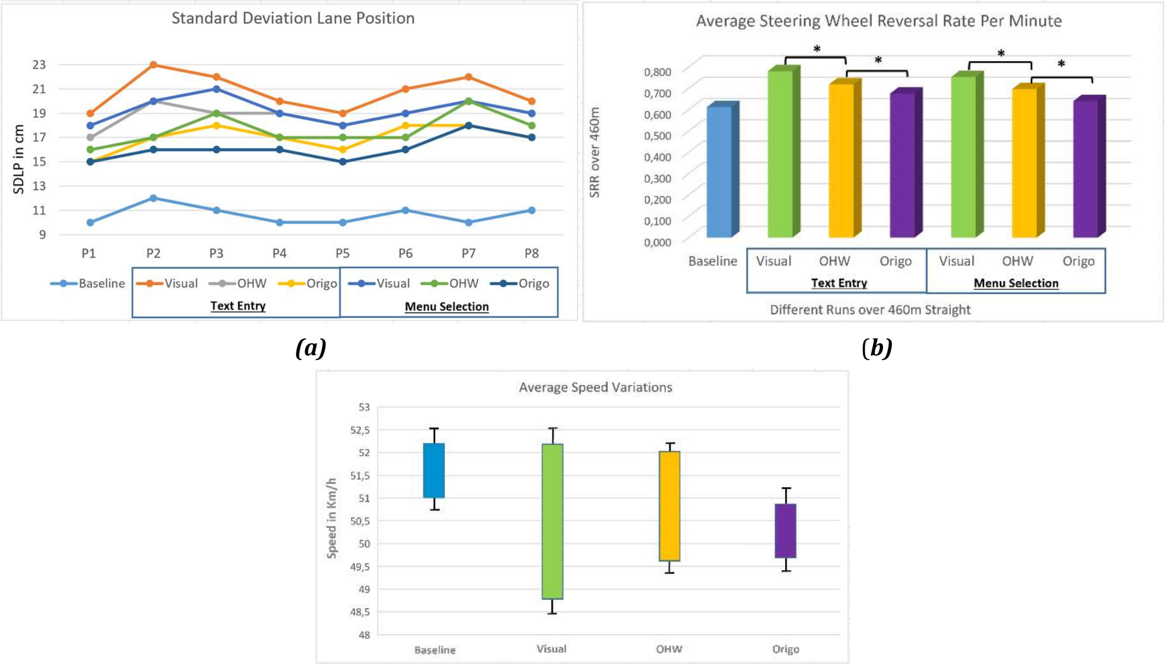


Figure 3: Left: The Porsche Cayenne Turbo on the *NTTT*; right: the *NTTT* section used for the user study.

4 RESULTS AND DISCUSSION

SSR was measured and calculated according to Markkula and Engstrom [23, 24] and SAE_J2944_appendices F [25] using a threshold of 2 degrees. SDLP was calculated as defined by Verster and Roth 2011 [26] and Green et al., [27], with reference to a visible white line in the middle of the track being recorded by a dash mounted camera and measurement taken at 2Hz. Looking at the Primary Task Performance, we see that SRR, SDLP and speed variation measurements [Fig. 4] clearly show that adding haptic feedback to the steering wheel improved primary task performance. Moreover, there was also a clear improvement between OSW and original wheel. Similarly, average speed variations showed drivers being better at maintaining the 60km/h with Origo wheel than OSW. Visual only had most distraction.



(a) *(b)*

(c)

Figure 4: Primary Task Performance measures. Error bars are "standard errors" and * indicates significantly different groups [repeated measures ANOVA; P<0.05]. (***a***) Standard Deviation Lane Position (SDLP) for each participant across all conditions and both secondary tasks; (***b***) Steering Wheel Reversal Rate (SRR) per minute for both tasks across all conditions; (***c***) the Average speed variations during each run for all conditions.

Secondary task performance measures provided similar results to Primary Task Performance, where Origo wheel yielded fewer errors and faster task completion times. Secondary task completion times, errors, and incompletes were lowest for OSW followed by OHW. Other measurements, including touch point accuracy (*above 80% accuracy*) as well as onscreen dwell times [28] also showed visual load was lowest for Origo steering wheel. And lastly, the OSW was better than OHW for both secondary tasks in lowering effort and frustration, and in increasing task performance, as measured with NASA TLX and analyzed using Friedman test [Fig. 5]. These results show that not only can the steering wheel be an ideal location to provide tactile input and output [29] but can also be enhanced to mediate the feedback ensuring reliable actuation for a wide range of application areas.

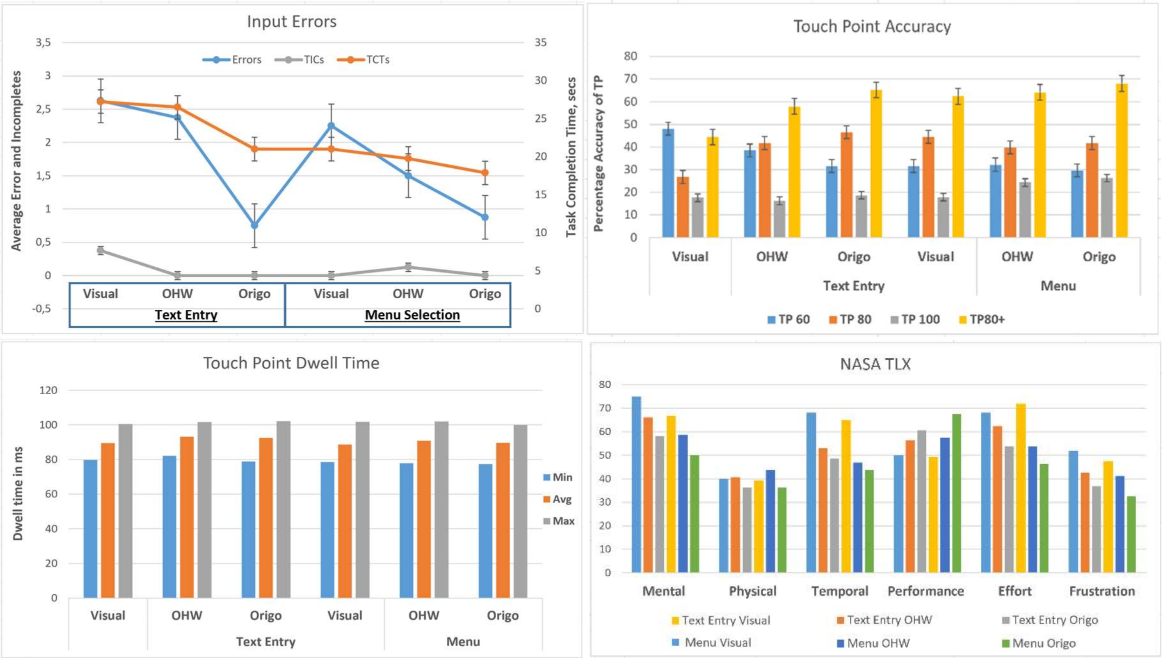


Figure 5: Secondary Task Performance measures: (top left) Input Errors, Task Incompletes, and Task Completion Times, (top right) Touch Point (TP) Accuracy, (bottom left) Touch point dwell times, (bottom right) NASA TLX 6-point evaluations.

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