Title:

Haptic Feedback for Automotive Touchscreen Display

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Introduction:

Touchscreen technologies, now ubiquitous in our daily lives, result from a long and continuous research and development process that traces back to the 1940s. Initially, touchscreen interaction required the use of a stylus. However, Eric Johnson brought the first conceptualization of a finger-driven touchscreen to life in 1965 [9]. This breakthrough technology made its commercial debut in 1980 when Hewlett Packard (HP) introduced the HP-150, a computer featuring a 9-inch CRT display with infrared detectors that could detect any finger interactions with the screen [1].

In automotive, adopting touchscreen technologies took longer than in other application fields. The first example was the 1986 Buick Rivera, with its Graphic Control Center [21], which was quite advanced and sophisticated. However, in 1990, Buick removed it because drivers needed to take their visual attention off the road for every simple action, like changing the temperature or switching the radio [10]. This determines the driver's distraction, significantly affecting safety and driving performance [19]. Interactions with IVIS (In-Vehicle Infotainment System) occur in a dual-task environment where any activity occurs while driving. Indeed, the main factors that determine the usability criteria of an infotainment system include environmental factors in addition to those related to the users and the activity itself [8]. The goal of interface design always remains to facilitate the primary activity, driving, and reduce interference from other activities and distractions. Efficiency is evaluated by comparing the time spent performing primary tasks with secondary ones.

Although this issue continues to be relevant, touchscreens are a vehicle standard. This trend reflects the ever-increasing growth in the complexity of infotainment systems, which makes it impossible to maintain a one-to-one mapping between function and button, paving the way to multifunctional systems [5, 11]. Kern and Pfleging describe three different interaction models with those systems, including touchscreens. Touchscreens allow direct interaction compared to the other models involving multifunctional controls (1), such as a touchpad and context-dependent buttons (2). This means that input and display are co-located [16]. In this case, locating the input requires significant visual attention because of the lack of tactile and kinesthetic feedback [5].

Literature review shows that introducing haptic feedback on a touchscreen can reduce visual attention requests during interaction and that a multimodal interaction, including visual, audio, and haptic feedback, is preferred by users [3, 15, 16]. Norman identifies two gulfs while a user is interacting with something. The gulf of the execution describes the moment users try to figure out what they can do and how a system operates. On the other hand, the gulf of evaluation identifies feedback and conceptual models that allow the user to understand what happened [14]. When introduced in touchscreens, haptic feedback is usually limited to confirmation of an action; it occurs once the target has been located on the screen [4]. For this reason, haptic feedback helps to reduce second glares after the input [16].

Haptic feedback can also be effectively used in the first phase of exploration. HapTouch is an example of this experimentation. Richter and others referred to the 0-2 state model proposed by Buxton to describe direct input devices as touchscreens. In this context, a system can be just in state 0, which means there is no interaction, or state 2 if a user touches the screen.; state 1, which corresponds to the system tracking the movement, is bypassed [6]. HapTouch investigates the necessity of differentiating tracking from activation. The authors propose a system in which touching and moving the finger on the screen corresponds to tracking while activating the user must perform a pressing action [20].

However, the role of haptic feedback, especially if integrated with others, in enhancing safety by reducing visual attention requests to perform secondary or tertiary tasks is understudied, yet the study on how to shape and optimize the feedback [4]. This research aims to fill this gap by describing actuators' selection and evaluation processes that are capable of giving different feedback forms. This investigation focuses on the vibrotactile method, which delivers direct vibration between the screen and the finger.

Methodology:

Haptic effect definition

To investigate haptic feedback for automotive touchscreen interfaces, we identified six foundational aspects that compose our vibration effects: duration and easing effect of the ramp-up phase, duration of the primary phase, duration and easing effect of the ramp-down phase, and total max amplitude of the vibration. From these different vibration parameters, four distinct haptic effects were individuated: Light Tick, Medium Click, Strong Click, and Ramp Vibration. Each utilized different vibration parameters to simulate better a particular tactile sensation needed to accommodate a broad set of scenarios, ranging from subtle to pronounced. These effects were then applied to simple touchscreen interactions, such as buttons, sliders, and stepped sliders, individually or in combination. By incorporating a variety of interactions, we aimed to assess the adaptability and performance of each haptic effect across different user interfaces commonly found in the automotive HMI field.

The individuation of the vibration parameters and the haptic effects was influenced by technical considerations and design guidelines set forth by industry leaders, such as Google [13] and Apple [17]. This choice to base our feedback designs on an already established guided line was twofold. First, they are widely used and established in real-world consumer products, although not in the automotive field. Second, this broad adaptation makes them expected by the end user, who is already used to them.

Actuator Selection

We identified and evaluated four distinct types of actuators; three of these were Linear Resonant Actuators (LRAs), and one was an Eccentric Rotating Mass (ERM). This selection considered factors such as compact design, availability, and prevalence in the field and aimed at providing a comprehensive understanding of the strengths and weaknesses of each type: Linear Resonant Actuators (LRAs) operate on the principle of resonance. They consist of a mass attached to a spring, creating a vibrating system. When an electrical signal at the resonant frequency is applied, the mass vibrates, producing the desired haptic feedback. Their quick response makes them suitable for delivering precise haptic effects, thus providing nuanced HMI feedback. Two LRA actuators (LRA-1 and LRA-2) had an oscillating mass on the Z-axis, normal to the touchscreen's surface, and one (LRA-3) on the X-axis, as shown in Fig. 1. These three actuators also have increasing vibration forces and require different current inputs.

On the other hand, eccentric Rotating Mass (ERM) operates based on a mass's eccentric rotation. An unbalanced mass is attached to a motor that spins rapidly, generating vibrations transferred to the device. ERMs are relatively simple and compact, making them cost-effective and easy to implement. However, they have limitations regarding the frequency range they can produce and limited precision in controlling the intensity and pattern of vibrations. This limitation on the quality of haptic feedback is problematic in applications that require fine-tuned vibrations, such as in our case. The study included an ERM to offer a comparative analysis against LRAs. Despite their weakness, ERMs could be preferred when simplicity, ease of implementation, and cost-effectiveness are necessary.

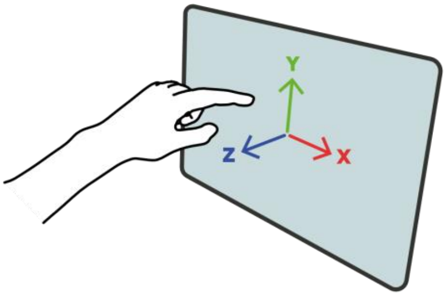

Fig. 1: Direction of the axis on the touchscreen.

Testing Setup

To ensure a comprehensive and realistic evaluation of haptic feedback in the automotive context, the study employed a driving simulator, a car-simulated environment designed to replicate key elements of car interior for automotive user experience evaluations. The simulator features two car seats, a steering wheel, and a central touchscreen display. This setup aimed to mimic the immersive experience of interacting with an actual car's human-machine interface, providing a more authentic testing environment. The central touchscreen display was the focal point for the haptic feedback evaluation. Through it, participants interacted with various interface elements, including buttons, sliders, and stepped sliders.

The hardware setup of the testing bench involved the four selected actuators positioned behind the central touchscreen display. This was a 16” LCD, with a resolution of 1920x1080 running at 60Hz with a 179° angle of vision. It weighed 2.24 kg, and its dimensions were 15 x 7 x 1 cm; a VESA mount was attached to the simulator structure. These actuators were connected to the haptic motor driver board Sparkfun DRV2605L [7] and the Arduino Nano 33 IoT board [2]. This hardware was connected with a serial interface to ProtoPie [18], running on a computer where the touchscreen was connected. Arduino controls the actuators with the proper vibration parameters for each effect. At the same time, ProtoPie managed all the touch interactions that the users performed on the touchscreen, the effects corresponding to each interaction, and all the Graphical User Interfaces displayed on the screen. The selection of this testing bench setup, as shown in Fig. 2, including Arduino Nano IoT boards and ProtoPie, was driven by the need for rapid prototyping. This combination offered a flexible and efficient platform for testing and refining haptic feedback and testing user experiences in a controlled environment. These tools allowed us to quickly integrate and iterate the touchscreen interactions and haptic effects, letting us easily modify the vibration parameters and rapidly test them iteratively.

Test Procedure

The test involved six participants, who were instructed to assume the driving position on the driving simulator, grasp the steering wheel, and imagine themselves in a driving scenario. They were also asked to talk aloud, comment on each effect perceived, and give them a verbal evaluation. Subsequently, they were directed to interact with specific graphical user interface (GUI) elements, such as buttons or sliders, depending on the haptic effect under investigation. This simulated interaction lasted for thirty seconds. Afterward, participants were prompted to complete a survey on the right part of the touchscreen, as shown in Fig. 3. Notably, the GUI elements and haptic feedback were presented on the left side of the screen, ensuring that participants could keep testing the haptic feedback even during the survey completion. In the test sequence, participants experienced each haptic effect individually before testing all impacts on a pseudo-real interface; in this phase, only the users' comments were recorded. After each testing run, participants were given a one-minute relaxation period before moving to the evaluation of the next haptic actuator, which followed the same procedure. Passive noise-cancellation headphones were utilized to isolate the participants, minimizing the potential influence of the audio noise produced by the actuators and ensuring that the focus remained on the haptic feedback.

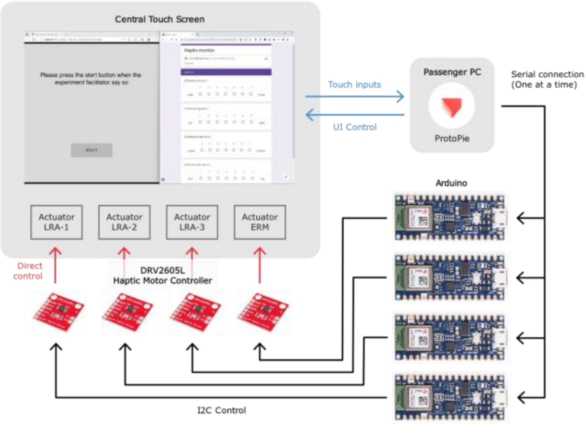

Fig. 2: Hardware setup.

Participants provided qualitative feedback on various parameters, including Force (Weak - Strong), Quality (Dirty - Clean), Reactivity (Delayed – Real-time), and Duration (Short - Long), by using a 7-point Likert scale. These items were derived from the ones of the User Experience Questionnaire (UEQ) by Hinderks et al. l. [12]; in addition, participants were encouraged to provide qualitative comments using the talk-aloud procedure to capture more nuanced aspects of their experience. These open-ended comments let participants articulate their perceptions, preferences, and any specific observations that numerical ratings might not fully capture. These were audio recorded and then analyzed.

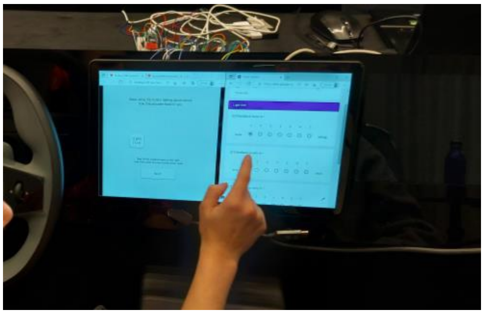

Fig. 3: User during the evaluation phase.

Test Results

Results from the surveys give several insights regarding the perceived effectiveness of different haptic effects applied to automotive touchscreen interfaces and in comparing different actuators.

The force evaluation shows that users perceive ERM actuators as weaker than Linear Actuators. This result was not expected; however, it could stem from the fact that this type of actuator is generally used on smaller surfaces. On the other hand, the perception of force for the LRAs actuators exhibited mixed results, depending on the effect considered. If indeed light tick results were similar, increasing the amplitude of LRA-2 is recognized as more powerful. Its characteristics expect this.

Conversely, when evaluating the free and stepped slider, the LRA-2 was perceived as weaker than the other two LRAs. Regarding quality value (Dirty—Clean), the ERM actuator exhibited underwhelming performance across all effects. Among the LRAs tested, LRA-1 was perceived as cleaner overall, followed by LRA-2 and LRA-3. A comparison of the LRA actuators for perceived Duration and Reactivity parameters shows no differences. On the other hand, ERM performed poorly on both parameters on all the effects.

Adjectives used by the users to describe the experience during the thinking aloud part mirror the survey results, with the ERM actuator performing poorly and being most described as “imperceptible” or “no feedback.” LRAs, the LRA-1, and LRA-2 perform similarly, with slightly better performance for the LRA-2 than the LRA-1. The LRA-3 was perceived as average, “dirty,” and “buzzy” more than the other LRAs and generally less powerful.

Conclusion:

This study aimed to explore and evaluate haptic feedback for automotive touchscreen interfaces by focusing on critical aspects such as haptic effect definition, actuator selection, testing setup, and the test procedure. By identifying and implementing four distinct haptic effects: Light Tick, Medium Click, Strong Click, and Ramp Vibration, and with carefully defined vibration parameters, we sought to simulate a range of tactile sensations suitable for diverse automotive user interface scenarios. Actuator selection involved the assessment of three Linear Resonant Actuators (LRAs) and one Eccentric Rotating Mass (ERM), intended to give an overview of the advantages and disadvantages of each type in providing haptic feedback in automotive touchscreen displays, with a particular focus on the exploration and evaluation for enhancing user experience.

To ensure a realistic evaluation, we employed a driving simulator emulating essential components of a car's interior. We have facilitated rapid prototyping and iterative testing of haptic effects, including a central touchscreen display connected to actuators controlled by Arduino Nano 33 IoT boards and ProtoPie software. This testing bench setup allowed us to assess user experiences in a controlled environment efficiently. The test procedure involved quantitative and qualitative analysis, using a survey based on a modified subscale of the UEQ and the talk-aloud procedure to comprehensively understand participants' perceptions, encompassing parameters such as force, quality, reactivity, and duration.

We also strongly acknowledge the test's limitations, including the small sample size and potential biases inherent in internal participants. To limit this, future studies could involve a more extensive and more diverse participant pool; additionally, by incorporating more sophisticated assessment techniques like Electroencephalography (EEG), Skin Conductance Response (SCR), and Electrocardiography (ECG), more profound insights into the perceived haptic effects on the driving user experience could be achieved.

In conclusion, this research contributes to the ongoing exploration of haptic feedback in automotive HMI by providing insights into the adaptability and performance of different haptic actuators with standard touchscreen interactions and haptic effects, focusing on the users’ experience that these could enable during the drive. It also reflects the importance for researchers and designers to consider factors beyond the mere characteristics of actuators in refining haptic feedback systems, thereby enhancing user experience and interface intuitiveness to improve driving experiences in the automotive sector.

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