Improvement of rotary encoders in human-machine-interfaces through optimized acoustic feedback

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Abstract: This work investigates the effect of the acoustic feedback of rotary encoders that are common in current human-machine-interfaces. The results are based on subjective trials in which the probands had to complete generic tasks using an encoder with programmable electro acoustic feedback. The tasks had to be performed with individually optimized feedback and two reference conditions. The results of the investigation showed the advantage of well-defined acoustic feedback on both accuracy and speed of task fulfillment.

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1. Introduction

In recent years, the increasing complexity of a modern car's infotainment and assistance systems led to new approaches in the user interface design. Menu-based systems that require multiple operations to complete a task have become the standard. The acceptance of this kind of interface is affected by different factors. A very complex menu structure and graphic design are criticized often by journalists and customers alike as are the input devices of the system. Control elements that are difficult to reach or that generally feel bad are disliked. The feeling of a control element can be considered as a mixture of acoustic and haptic impressions. Modern cars—especially in the premium segment—are considered as lifestyle products that are supposed to evoke the impression of high quality.

This work describes an approach for the definition of an optimized acoustic feedback of a rotary control element that is the typical main input device of modern car's user interfaces. Furthermore, the work explains the effect of the acoustic feedback on the speed and accuracy of operation and hence the usefulness of optimized acoustic feedback.

2. Experimental setup

The operator of a button experiences several impressions during the operation. The material and the surface texture, the change of momentum, and the audible feedback. All of these impressions occur in combination and are difficult to change, i.e., the momentum of a rotary encoder without changing its audible feedback. Based on this knowledge, an encoder with electronically adjustable acoustic feedback as well as a simulation model for the synthesis of feedback signals has been derived. This approach is similar to the approach of Reisinger *et al.* (2006) in the field of haptics. The model is optimized (re)synthesizing click sounds based on relatively few input parameters. The parameters can be taken from data extraction of sampled natural sounds or from the input of test subjects.

2.1 Signal synthesis

The model is based on an algorithm originally proposed by Gaver (1993) for the synthesis of auditory icons. Gaver's model uses several sine-wave oscillators with exponential damping. A previous experiment (Treiber and Gruhler, 2008) showed that subjects generally prefer stimuli that are based on broadband signals over stimuli based on harmonic signals. For this reason, sine oscillators have been replaced with wavetable oscillators that use third-octave-band noise. Furthermore the importance of the logarithmic attack phase of a transient signal (as described, i.e., by MacAdams, 1996) led to the introduction of an attack parameter. To keep the number of required input parameters as low as possible, the frequencies of the wavetable oscillators have been locked to the center frequencies of the third-octave-bands according to DIN EN 61260. As pre-studies showed, the encoders typically used show no relevant signal components below 1 kHz. For this reason, only 15 oscillators have been used in this study.

2.2 Signal playback

The synthesized sounds were played back using a rotary encoder with adjustable acoustic feedback. The encoder itself has very little friction and no audible feedback. Furthermore it features a resolution of 256 increments. Typical encoders for user interfaces feature 16-24 increments per rotation. The encoder is connected to the control PC via a microcontroller that translates the high resolution signal of the encoder to a resolution of 16 increments per rotation. The resulting signal is sent to the PC and triggers the sound playback. The high-resolution input is used to avoid multiple sound playbacks if a subject jitters.

To perceive the acoustic feedback in a realistic way, the playback of the stimulus has to occur within a certain time frame after the sound is triggered. The research of Adelstein (2005) showed that the acoustic feedback has to occur within 25 ms after a haptic sensation. This constraint has to be kept even though in this study no haptic feedback is used because playback of sound longer than 25 ms after a subject has stopped turning the encoder has to be avoided.

For this reason, the playback of stimuli is performed on a real-time LINUX system using the JACK audio environment and PUREDATA. The synthesis of stimuli is performed in off-line MATLAB every time the subject adjusts the parameters.

For spatial congruence, the loudspeaker used for playback is placed vertically over the rotation axis of the encoder so that there is no displacement on the horizontal plane. The displacement on the median plane is 7.5° and hence within the constraints presented by Altinsoy (2006).

The subjects operate the encoder typically with the right hand, the center axis of the loudspeaker is aimed at the subject's right ears. The stimuli are presented in a quiet environment with a reverberation time of 0.2 s. The reverberation time is frequency independent in the relevant frequency band.

3. Experimental design

The experiment is divided into two parts. At first the subjects' task was to adjust the acoustic feedback in a specific way they like. In the second part, the task was to adjust a value with the encoder as fast and as accurate as possible. This task had to be fulfilled with the previously adjusted feedback, no acoustic feedback and a 4 kHz sine burst which is 15 ms long and played back at 80 dB(A). This stimulus provides very clear but is very unpleasant as a previous study shows (Treiber and Gruhler, 2008). Twenty-one subjects took part in the study.

3.1 Optimized feedback signal

In this part of the experiment, the subjects were asked to adjust the acoustic feedback using three parameters to describe the signal. The subjects could adjust the overall spectrum of the sound, the overall amplitude, and the decay time of the signal. These

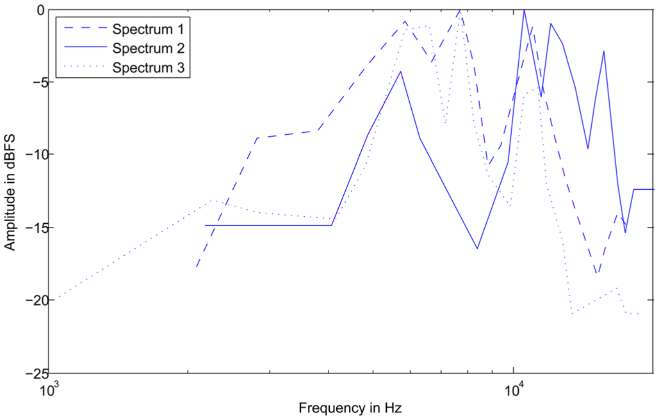

Fig. 1. (Color online) The three spectra which were available to the subjects. Spectrum 2 was preferred by two-thirds of the subjects.

three parameters proved to be most important for the acceptance of a click sound in a previous work (Treiber and Gruhler, 2009). The spectrum had to be set by choosing one of three available spectra; the other parameters were adjusted using a 2-AFC procedure. The three available spectra (see Fig. 1) were based on averaged measurements of three different types of encoders. Several thousand individual clicks have been acquired for each type on a purpose-built robotic actuation unit (Treiber and Gruhler, 2007).

3.2 Speed and accuracy of operation

In this part of the experiment, the subjects' task was to turn the encoder by a given amount of increments in a given direction as fast and as precise as possible. The target values that had to be reached were 1; 3; 5; 10, and 20. The numbers could occur also as negative; in this case, the subjects had to turn counterclockwise. The lower values are likely to occur in menus, the higher values are typical for long telephone or media lists in automotive HMIs. The subjects were presented two numbers on the display: the current position and the target value. After the target value had been reached, the subjects had to confirm, the current position was reset to 0 and another target position was displayed.

Each target value was played back three times in combination with all three feedback conditions (no feedback, desired feedback, unpleasant feedback). Furthermore, all target values and all stimuli have been presented to the subjects in 10 primer tasks, leading to a total of 100 tasks that were typically completed in maximum 5 min. The randomized order of target values was the same for all subjects but the assignment of stimuli rotated to avoid training effects. The procedure for the assignment is explained in Table 1.

4. Discussion of results

4.1 Speed of operation

As can be seen in Fig. 2, 13 of 21 subjects were the quickest with their individually setup sound, whereas only 3 subjects were quickest without any acoustic feedback.

On average, subjects were 74 ms quicker when feedback was present. Interestingly, the subjects are on average 33 ms quicker with their individual feedback signal than with the very loud but annoying sound. This proves that it is not only interesting from a marketing point of view to provide pleasant feedback but from a usability perspective and ultimately from a safety perspective as well. While the relative gain in

Table 1. Excerpt of the assignment of acoustic stimuli to task number.

Task Nr.	Target value	Stimulus for subject n	Stimulus for subject n+1	Stimulus for subject n+2	Stimulus for subject n+3
11	−5	1	2	3	1
12	10	1	2	3	1
…	…	…	…	…	…
19	−20	1	2	3	1
21	−1	2	3	1	2
…	…	…	…	…	…
31	3	3	1	2	3
…	…	…	…	…	…
41	1	1	2	3	1
…	…	…	…	…	…
100	20	3	1	2	3

Note the repetition after three subjects and rotation of sounds every 10 tasks.

task speed seems negligible as the average task duration was about 2500 ms, the absolute gain is still relevant in an automotive environment because it means that the driver can focus on the road again sooner. At typical motorway speeds this time amounts to approximately half a car-length. Regarding the accuracy of the subjects, it is also the self-defined stimulus that leads to the best performance.

4.2 Accuracy of operation

To analyze the accuracy, the absolute dialed in value is subtracted from the absolute target value, i.e., it would have been an error of 1 if the proband dialed in 6 instead of 5 but also if the proband dialed in -6 instead of 5. This has been done because some subjects occasionally turned the knob in the opposite direction than required by the sign. Because this experimental setup did not use any meaningful graphic interface that had to be operated through the input device but only used abstract numbers, it is valid to use the absolute values. The subjects typically performed best using the self-defined feedback, while the clearly audible but unpleasant feedback increased the rate of error to almost twice the result that was observed using the individually optimized stimulus. The results are summed up in Table 2.

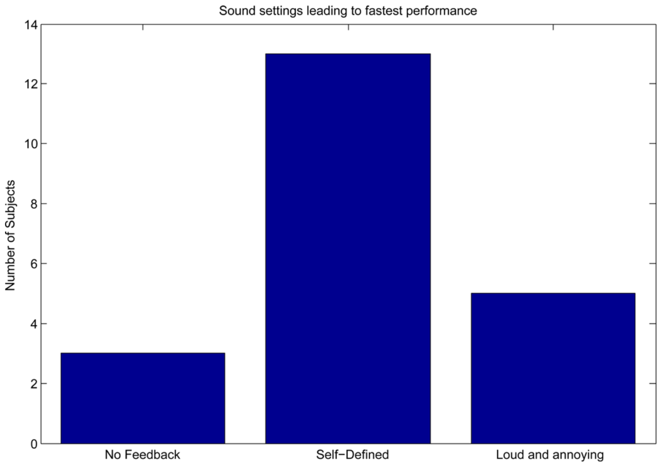

Fig. 2. (Color online) The majority of subject performed fastest with the self-defined auditory feedback signal.

Table 2. This table sums up the results of the experiment regarding the effect of pleasant auditory feedback on both accuracy and reaction time.

Acoustic feedback	Mean error in detents	Mean reaction time in ms
None	1.00	2200
Self-defined	0.67	2141
4 kHz burst	1.24	2170

5. Outlook and future work

The results of this work suggest an improvement of usability through well-designed acoustic feedback. However, as the design of experiment isolated the acoustic stimulus from tactile and visual cues, the results raise the question, whether or not the positive result of the acoustic feedback can be transferred to input devices with tactile feedback and if the settings for optimized sounds depend on the tactile and visual cues such as the diameter or the material of the knob. Furthermore, the sounds were presented in a quiet environment with no other tasks for the subjects (i.e., driving a vehicle). The architecture of the presented acoustic simulator allows it is integration in more complex experiments for cross modal studies and/or within the context of a driving simulator.

Additionally, the presented approach of designing individually optimized feedback sounds provides a method for acoustic rapid-prototyping for both electromechanical control elements and the increasingly important area of touch-sensitive devices.

Acknowledgments

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