Simulating Push-Buttons Using a Haptic Display: Requirements on Force Resolution and Force-Displacement Curve

C. Doerrer, R. Werthschuetzky
Institute of Electromechanical Design / Darmstadt University of Technology
Merckstrasse 25 , 64283 Darmstadt , Germany
c.doerrer@emk.tu-darmstadt.de

Abstract

This paper presents the procedure and results of two experiments dealing with the force resolution of the human finger and with haptic demands on push-buttons. The outcome is used to specify design details of a novel approach to a flexible control panel.

A haptic display controlled by a PC enables the simulation of push-buttons with programmable force-displacement curves. The "just noticeable force difference" is investigated by displaying a constant force with changing value in the middle of the stroke. On average the participants were able to perceive a sudden change of force larger than 100 mN. In relation to the reference forces between 0,5 and 2,5 N this equals a relative noticeable force difference of 20 to 5%.

In the second experiment the participants could vary the force-displacement curve of the simulated button. They were asked to find a setting that provides a subjectively appropriate haptic feedback during the depressing.

1. Introduction

Technical devices in everyday life like ticket-machines, cash-dispensers, telephones, hi-fi- and TV-sets, etc. keep coming with an ever increasing number of features. This extended functionality involves a major problem for the man-machine interfaces, as every function needs to be selected and controlled by the user. Menu-based user interfaces are a common solution for handling the large amount of features. They are based on the idea not to offer all selectable functions at once, but to split them into different levels. So the control panel requires only a small number of buttons and therefore stays clear and manageable. But menu-driven handling is only possible with special input/output devices. They need to provide control elements with programmable functions and ideally with a variable number of menu items. Touch screens offer these features. Their virtual push-buttons are freely configurable in number, size, and appearance.

The most prominent disadvantage of touch screens is the missing haptic feedback that ordinary mechanical push-buttons naturally provide in contrast to the virtual buttons displayed on touch screens. People are used to feel a "haptic click" as a confirmation of the fact that they have successfully pressed the button. Touch screens need to substitute this sensation by visual or acoustic signals. But these don't match the user's expectations of a haptic feedback, which is essential for an intuitive and automatic operation of control elements without the need of conscious attention.

Therefore we envisage a new approach to build a control panel that combines the flexibility of touch screens with the haptic stimuli of ordinary push-buttons. The panel consists of an array of numerous segments, each representing an actuator-sensor-system. Hence the position and exerted force of every segment can be controlled independently from each other. As shown in figure 1, different numbers of buttons with various sizes are possible to provide. These buttons can actually be pushed down, while they generate a programmable resistance, which needs to be overcome by the user. So the desired haptic feedback to prevent uncertainty and enable fast and comfortable machine controlling is provided [1][2][3]. The new approach is presented in detail in [4].

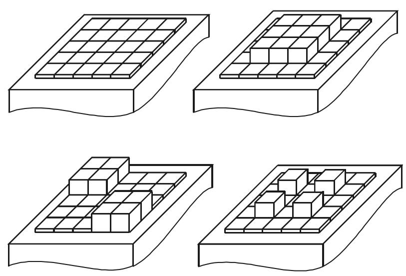


Figure 1. Sketch of a control panel with buttons variable in number and size. The panel comprises of single segments, each representing an independent actuator-sensor-system.

2. Experimental Set-Up

Before the planned control panel can be developed in detail, some preliminary examinations are necessary to investigate the requirements on the actuator-sensor-system of the single segments. In order to design the actuator, its required performance referring to the maximum force and the force output resolution needs to be known. Two experiments are carried out. The first one examines force differences which people are just able to perceive during depressing a push-button with a finger. The second experiment deals with the force-displacement curve of a push-button, which is the characteristic course of the force during the depressing. The goal was to find out about the demands on a user-friendly button.

To perform these investigations a test apparatus is required. We designed a device to simulate a single push-button with the opportunity to change its characteristic curve. That means it is possible to freely configure the force exerted by the button depending on its position. The apparatus illustrated in figure 2 and 3 – called "key-simulator" – mainly consists of an electro-dynamic actuator and an inductive positioning-sensor with a resolution of 10 µm. A key is attached to the actuator. It can be moved up and down and exerts a programmable force when pressed by a finger.

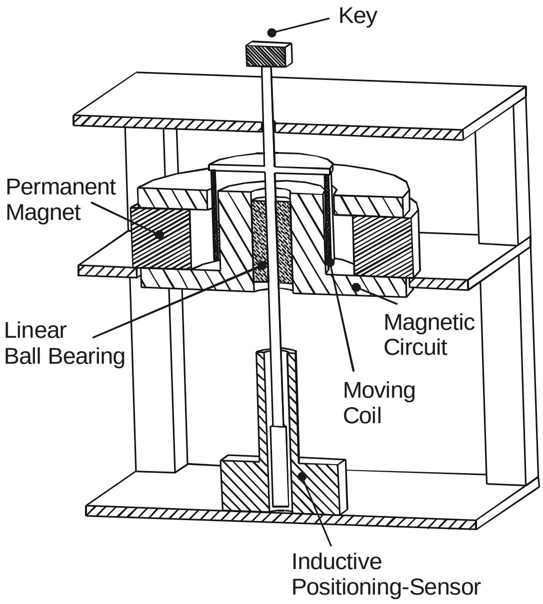


Figure 2. Sketch of the key-simulator.

The overall experimental set-up is depicted in figure 4. The system is controlled by a personal computer. The software controller is programmed using a software system called LabVIEW. It evaluates the position of the key and calculates the required current for the actuator in order to exert the desired force. There is no need of a force sensor or a closed loop force controlling, as the electro-dynamic actuator ideally generates a force proportional to the electric current.

The set-up offers the performance of simulating a push-button with an adjustable stroke up to 10 mm, and a variable output force with a maximum of 12 N. Due to the mechanical layout of the apparatus, the exerted force is not fully in a linear relation to the electric current. Therefore comprehensive measurements of the exerted force in dependence on the current and the position of the key were performed in a range of 0 to 5 N. It showed that the absolute value of the force differs not more than 85 mN from the supposed linear calculation. But at a constant position of the key, the relative difference between two exerted forces is calculable with an accuracy better than 10 mN by evaluating the flowing currents. In the first experiment this value of 10 mN can be assumed as the uncertainty of the force determination.

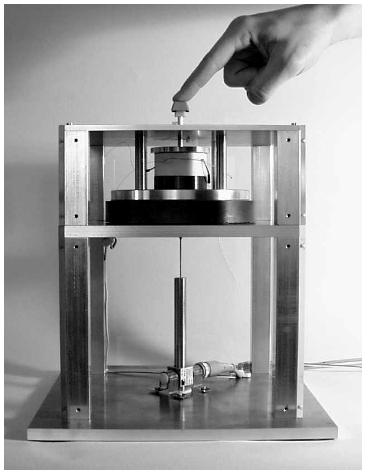


Figure 3. Picture of the key-simulator.

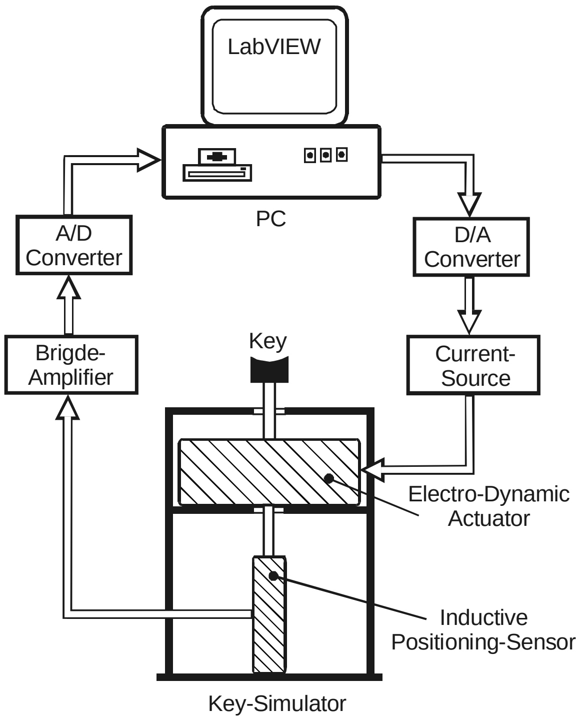


Figure 4. Diagram of the experimental set-up.

3. Force Difference Experiment

3.1. Method of Experiment

The goal of this experiment is to determine the difference in force a human finger is able to detect while pushing down a button (Just-Noticeable-Difference = JND). Therefore the key-simulator displays a course of the force as illustrated in figure 5. The force is constant both in the upper and in the lower part of the stroke, but shows a sharp rise or fall at the transient in the middle. The task of the participants is to push down the key-simulator in a full stroke and decide whether they could feel a change of the force or not. The amount of the force in the upper part of the stroke (test force) can be varied by the participants, whereas the force in the lower part is fixed (reference force). The aim is to find the setting, when they just couldn't sense any change of the force at the transient of the test force to the reference force.

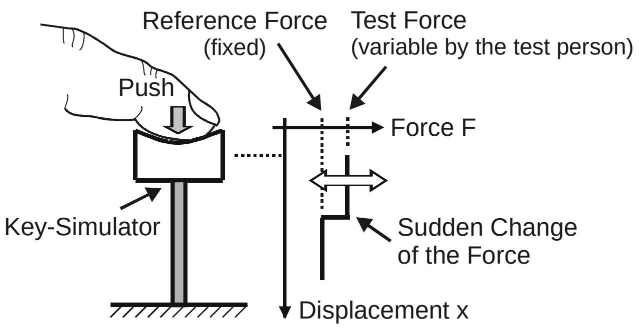


Figure 5. Course of the force during the force difference experiment.

For the experiment the participants could increase or decrease the amount of the test force in fixed steps of about 10 mN by using the computer keyboard or the computer mouse. They were allowed to vary the test force as often as they liked. While doing so they could always depress the key and check if the force feels constant or not.

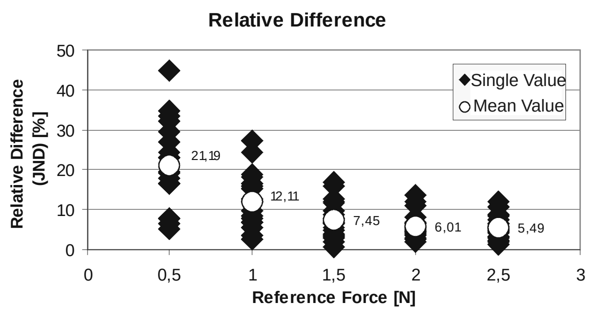
In this way the participants had the opportunity to exceed or to undershoot the just noticeable force difference, so that the change of the force was either clearly perceivable or clearly not. But it was essentially important that they would finally find the setting with the largest possible difference between test and reference force, which they still could not distinguish. That means in this setting the participants had the impression of a constant force during the depressing, but if the difference between test and reference force would be increased for just one step (10 mN), a change of the force at the transient would be perceptible.

20 test persons - 18 males, 2 females - participated in the experiment. All of them were between 24 and 32 years old. They were told to put their preferred hand on a special rest to guarantee a similar hand position for all test persons. With the index finger the button of the key-simulator had to be pushed down. The test persons were instructed to move the finger slowly and to concentrate upon the force perception in the finger. This is important because the sensitivity probably depends on the velocity of the movement. Moreover the participants should not watch their finger during the experiment, as it is possible to notice visually an interruption of the continuous finger movement if the force of the button changes.

The experiments were carried out at five different reference force levels: 0,5; 1; 1,5; 2; and 2,5 N. This is a reasonable force range for push-buttons. At each reference force level the just noticeable force difference should once be determined for a test force smaller than the reference force and once for a bigger one. This results in 10 trials per participant. The order of the displayed reference force was chosen randomly. The difference between reference and test force at the start of each trial was also randomly distributed between 35 and 150% of the reference force. During the experiments the stroke of the key-simulator was adjusted at 5 mm. The transient between the two forces took place in the middle of the stroke.

3.2. Results of Experiment

The results of the force difference experiments are shown in figure 6. For each participant the absolute values of both trials at one reference force (test force larger and smaller) are averaged.



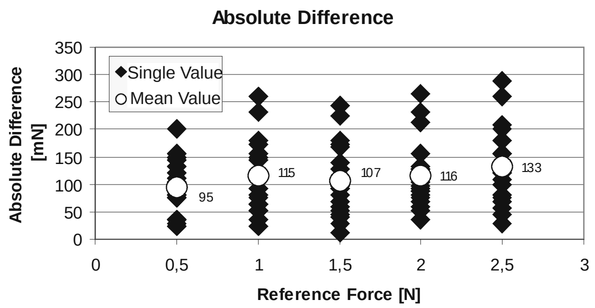


Figure 6. Results of the force difference experiment: Relative and absolute differences between test and reference forces.

The relative difference between the test force and the reference force represents the “just noticeable force difference” (force-JND). It is obvious, that this JND increases with lower reference forces. A similar behaviour HASSER found regarding experiments about the force output resolution of the human hand: Subjects can control larger forces with a smaller percentage error than smaller forces [5].

Moreover it becomes apparent that for higher reference forces the mean JND approximates the value of about 5-10%, mentioned by TAN as an average force-JND for the human hand [6].

The absolute difference between test and reference forces is interestingly almost constant at about 100 mN.

For the interpretation of the results of the experiment it should be considered, that the participants could vary the test force only in fixed steps of 10 mN. Moreover they stated in a following questionnaire that it was difficult to decide for one exact setting. An uncertainty always remained, whether the change of the force is perceivable or not. So a random error of at least one step, what equals 10 mN, should be taken into account.

The questionnaire showed as well that the test persons enjoyed the experiment and that they didn’t lose their patience. This surely is a result of the active way they were involved in the investigation. They varied the test force at their own will and therefore could control how fast and how often this happened. This increases the motivation and prevents boredom.

4. Force-Displacement Curve Experiment

Figure 7 shows a typical force-displacement curve of a conventional mechanical push-button. It illustrates that the force needed to depress the button is not constant but varies in dependence on the displacement: Starting from the initial position the resistance rises up to the switching point of the button, followed by a distinct decrease. This characteristic curve provides the typical “haptic click”, supporting an intuitive operation.

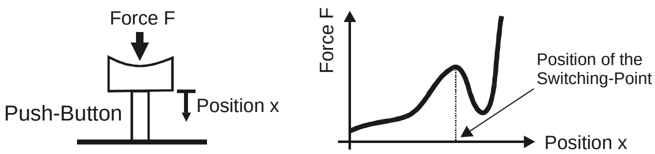


Figure 7. Characteristic force-displacement curve of a conventional mechanical push-button.

4.1. Method of Experiment

The second experiment investigates the user’s demands on the characteristic curve of a push-button. What does it have to be like to provide an unambiguous haptic sensation? To answer this question the key-simulator is used to display a push-button with variable force-displacement curve. The test persons can change this curve and check its effect to the haptic behaviour by depressing the button. In reality the course of the characteristic curve is very complex. In order to make the task easier for the participants, the number of possible settings is limited by simplifying the curve as shown in figure 8. It consists of five straight sections, variable by six parameters. Furthermore the constant force for the way back from the end stop to the initial position can be modified. The test persons can change these parameters by using virtual sliders displayed at the computer screen as depicted in figure 9.

The forces can be set in a range between 0 and 3 N, the positions in a range between 0 and 5 mm. The sliders of the graphic user interface thereby enable an accuracy of adjustment of about 50 mN, respectively 0,1 mm.

The same 20 participants took part in this experiment. They were allowed to change and check the curve for unlimited time until they found the subjectively most convenient characteristic. The instructor encouraged the participants to check many different characteristics and to change just one single parameter before testing the behaviour of the button again.

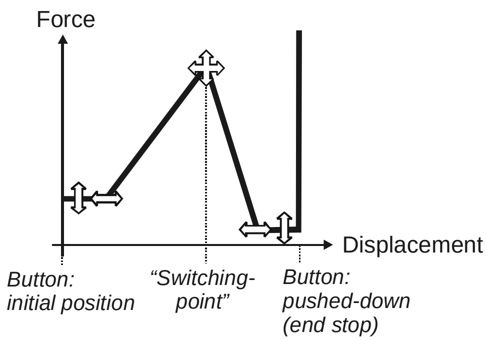


Figure 8. Setting parameter of the force-displacement curve experiment.

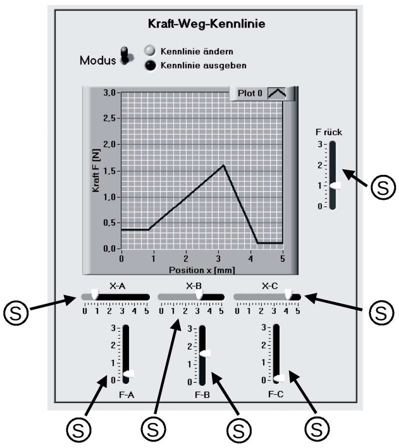


Figure 9. Virtual sliders (S) to modify the characteristic curve of the simulated button.

4.2. Results of Experiment

The results of this experiment are partly depicted in figure 10 and as an overview in figure 11. Before drawing some consequences, the limitations of this experimental approach should be considered: The simplified characteristic curve is not able to provide a haptic impression as smooth and accurate as the more complex course of real existing push-buttons. Still the simulated push-button gives a unique haptic feedback and does not feel unusual. Another more critical point is the large number of possible settings. Even with the reduced number of seven parameters to vary the force-displacement curve, a large search space is offered to the participants. They might terminate at a local best rather than the global best setting. But observing the participants during the experiment showed, that they carefully and patiently checked a lot of totally different characteristics within 10 to 20 minutes. Hence the results are probably a good basis to investigate the demands on push-buttons, even if it cannot be guaranteed that the test persons finally found their absolute best setting. As this was considered in advance, another questionnaire had been prepared. Participants could write down a range for every parameter, within which they subjectively feel comfortable with the haptic behaviour of the push-button. Nevertheless they should finally decide for one particularly good setting, which are shown in figure 11.

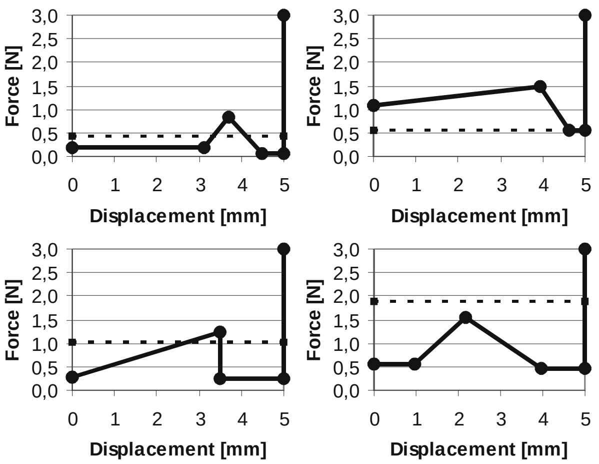


Figure 10. Examples of force-displacement curves, set by four test persons. It is clearly visible that people prefer very different characteristic curves of push-buttons. The dotted line indicates the constant force for the backward movement.

Even though the curves of the different participants are hard to compare, most of them show some similarities: For example the maximum force is mainly not much larger than 1,5 N (figure 12); the increase of the force to the switching-point amounts to about 1 N, as well as the following decrease of the force, etc.

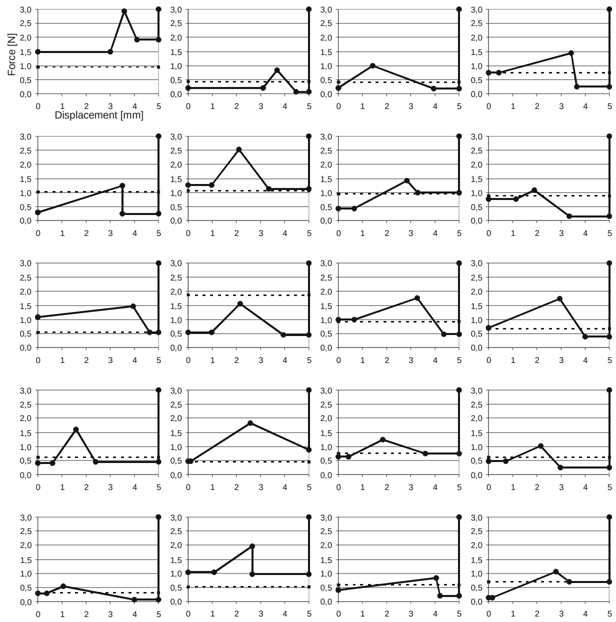


Figure 11. Overview of the preferred force-displacement curves of all 20 test persons.

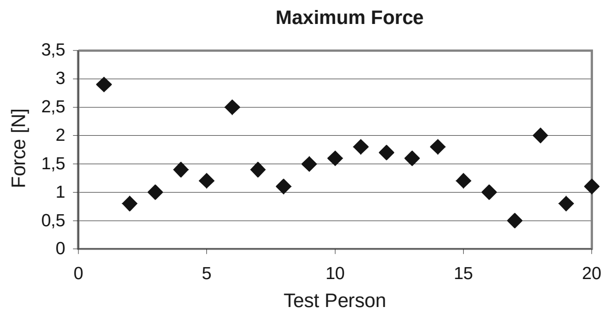


Figure 12. Maximum force set by the different test persons at the switching point of the simulated push-button.

Further investigations could deal with more detailed examinations of some single characteristics of the curve. For instance only the rising gradient could be varied in order to specify the user's most preferred one, while the rest of the curve remains unchanged.

Finally an important statement of the participants should be mentioned: The preferences of the haptic behaviour of a push-button depends on the field of its application. A button for a keyboard needs other characteristics than for a remote-control. In this experiment the participants were told to imagine the button to be used in a ticket-machine.

5. Summary and Conclusion

The just noticeable force difference of the human finger during depressing a button showed an increasing sensitivity with rising reference force. In a range between 1,5 and 2,5 N of the reference force, the determined mean JND approximates a value between 7,5 and 5,5%. This is close to the value of 5 to 10% stated by TAN [6].

Both experiments are meaningful to draw some conclusions particularly for the design of the presented approach to a novel control panel. The actuators used for this application need to exert a maximum force of at least 1,5 N, as most of the characteristic curves set by the participants have a peak force in this range. In other words a force of at least 1,5 N is required for a unique haptic feedback of push-buttons, which satisfy most users' expectations.

Referring to SHIMOGA, a high quality force reflecting device must have a sensitivity at least 10 times better than that of the human finger [7]. Considering the results of the force difference experiment (a noticeable absolute difference of 100 mN), a resolution of 10 mN for the actuator seems appropriate, which has been stated by SRINIVASAN as well [8].

Altogether the results of the force-displacement curve experiment support the novel approach to the presented control panel. It enables an individually adjustable characteristic of the push-buttons, what is obviously necessary to satisfy the user's different haptic demands.

6. References

[1] H. Rühmann, "Stellteilgestaltung", in H. Schmidkte (Ed.), *"Ergonomie"*, 3. Edition, Hanser Verlag, München, 1993, pp. 554-562.

[2] S. Münch, and R. Dillmann, "Haptic Output in Multimodal User Interfaces", *Proceedings of the International Conference on Intelligent User Interfaces*, Orlando, Florida, 1997, pp. 105-112.

[3] K. Baumann, and H. Lanz, *Mensch-Maschine-Schnittstelle elektronischer Geräte*, Springer-Verlag, Berlin, 1998.

[4] C. Doerrer, and R. Werthschuetzky, „A New Approach to Operating Machines with high Functionality", *Proceedings of Eurohaptics 2001*, Birmingham, Great Britain, 2001, pp. 105-107.

[5] C. Hasser, "Force-Reflecting Anthropomorphic Hand Masters", Interim Report, Crew Systems Directorate Biodynamics and Biocommunications Division, Wright-Patterson Air Force Base, Ohio, 1995.

[6] H. Tan, X. Pang, and N. Durlach, „Manual Resolution of Length, Force, and Compliance", *ASME Advances in Robotics*, 1992, vol. 42, pp. 13-18.

[7] K. Shimoga, "A Survey of Perceptual Feedback Issues in Dextrous Telemanipulation: Part I. Finger Force Feedback", *Proceedings of the IEEE Virtual Reality Annual International Symposium (VRAIS)*, Seattle, Washington, 1993, pp.263-270

[8] M. Srinivasan, and J. Chen, "Human Performance in Controlling Normal Forces of Contact with Rigid Objects", *ASME Advances in Robotics, Mechatronics, and Haptic Interfaces*, 1993, vol. 49, pp. 119-125.