Interaction-based Dynamic Measurement of Haptic Characteristics of Control Elements

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Abstract. The force-displacement curve is typically used today to haptically characterize control elements. Elements with the same curve, however, may still lead to quite different percepts because the curve describes only static information. To overcome this limitation, a new dynamic measurement method is introduced. It can directly measure dynamic interaction signals between a finger mimicking measurement device and control elements. Using this measurement method, also novel control elements like touchpads with active haptic feedback can be technically specified and evaluated for the first time.

Keywords: Haptic perception, haptic measurement, finger interaction, automotive switch, touchpad

1 Introduction

The haptic feedback of control elements such as push buttons, rotary controllers, touchscreens or touchpads plays an increasingly important role in the development of modern human machine interfaces. In this work, we focus on linearly actuated control elements, for example push buttons and touch interfaces with active haptic feedback. To specify and evaluate their haptic characteristics, static measurements i.e. force-displacement curves are frequently used, for example in automobile industry ([1]-[3]). However, such curves describe only the static properties of control elements and thus, cannot capture dynamic effects which can also be perceived by humans (see [4] and references therein). Thus, control elements, which have the same static properties, but still feel differently due to their different dynamic properties, cannot be specified using the static description.

In order to analyse the effects of the dynamic behavior of control elements on the haptic perception and to specify the desired dynamic behavior for their design, we need to be able to characterize the dynamic interaction taking place between control elements and the human interacting with them. In this paper we introduce a novel haptic measurement method that measures dynamic interaction signals between a control element and an instrumented robotic probe.

Using this new interaction-based dynamic measurement method, dynamic haptic characteristics of control elements can be captured very efficiently.

The remainder of the paper is organised as follows: Section 2 gives a brief overview of the static measurement and its shortcomings. Section 3 introduces the newly proposed interaction-based dynamic measurement method, the effectiveness of this method is demonstrated by application examples. In Section 4, the paper is concluded by a discussion and outlook.

2 Static Measurement and Problem Formulation

A common method to measure force-displacement curves is using a positioning system with a rigid probe to push the control element with a constant velocity ([1]-[3]), as shown in Fig. 1(left). The pushing velocity has to be chosen low (usually around 0.1 mm/s) so that dynamic effects of control elements due to inertia or damping are negligible and only stationary behavior is captured. From the force-displacement curve, technical features like lead travel and switching force (Fig. 1(right)) are derived and correlated with subjective impressions such as “clear”, “comfortable” or “high-quality” by psychophysical studies [3]. Note that this curve describes only static properties i.g. the stiffness of control elements.

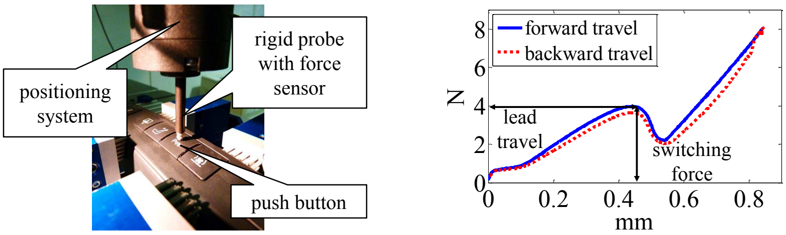

Fig. 1. Static measurement for a push button: Measurement device (left); Force-displacement curve and technical features derived from the curve (right).

However, when pushing a button, the interaction between the finger and the control element is a dynamic process and the interaction force applied on the finger and perceived by the human depends not only on the stiffness of the control element, but also on its dynamic properties e.g. inertia or viscoelasticity. Thus, control elements with the same stiffness can still feel differently due to different masses or damping levels, although their static measurements are the same (see Fig. 2 for an example). Thus, static measurements are not sufficient to capture all haptic characteristics of control elements.

Furthermore, over the past decade, control elements have no longer been limited to passive elements. Diverse new concepts have been developed, for example, touchscreens and touchpads with active haptic feedback. The feedback

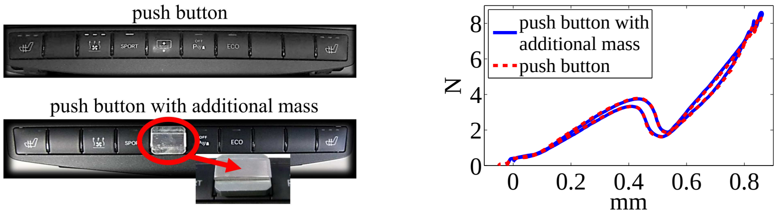

Fig. 2. Two push buttons (left), one of them with additional mass (2.5 g), feel differently, but their static measurements (right) are the same.

of such touch interfaces can be generated by different types of actuators like vibrators of a smartphone or in-plane-microactuators deforming the touch surface or electromagnetic actuators displacing the touch surface supported by a spring element. In Fig. 3(left)), the concept of an electromagnetic actuation is shown. The stiffness of such touchpads can be described by a progressive spring, which means that, unlike push buttons, there is no snap (a drop in reaction force) in the static force-displacement curve. Furthermore, two mechanically identical touchpads can still lead to different percepts, because the actual snap is caused by an impulse-like feedback force controlled by the actuator. If this force is generated differently, the touchpad will feel differently, although its stiffness is the same (see Fig. 3(right) for an example). Again, the static measurement can not capture these dynamic haptic characteristics.

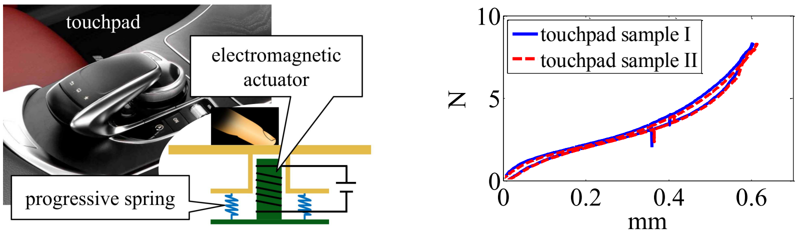

Fig. 3. Touchpad with active haptic feedback (left); Two equal touchpads with different feedback forces feel differently (based on the subjective impression of 5 subjects: one snap feels strong and the other feels weak), but they have the same static force-displacement curve. In the curve, no snap can be found, but only a small spike (right).

To measure the dynamic properties of control elements, one might consider using the static measurement device to excite the control element and then identify its dynamic parameters. However, to sufficiently excite the control element, the input signal must be highly dynamic and, at the same time the total travel of a control element is usually very short, which means that a highly dynamic measurement device with a very high sampling frequency is necessary. More importantly, there are diverse types of control elements with different mechanical structures and actuation concepts and it is difficult to find a general model structure to describe all of them. Thus, an appropriate model structure for each specific control element type has to be found first, before identifying them. Furthermore, due to the different models, different parameter sets are needed to be identified, which leads to the problem that the correlation between subjective impressions and one particular parameter set is only valid for the particular control element type and cannot be used to specify and evaluate other types. In other words, different control element types need different characterizing frameworks. Thus, to overcome these restrictions of static measurements and the drawbacks of a classical parametric identification of control elements, a new measurement method is needed.

3 Interaction-based Dynamic Measurement

A new *interaction-based dynamic measurement method* is introduced. The main idea of this method is that instead of directly identifying dynamic parameters of control elements, the element is characterized indirectly by features derived from dynamic interaction signals between the human finger and the control element. Considering the human finger as a mechanical system, this system is excited by the interaction force applied on the finger. By measuring this force along with the displacement and its derivatives, the dynamic haptic characteristics of control elements can be captured indirectly. The interaction depends not only on the control element but also on the finger as they are two physically coupled dynamical systems and the dynamics of one affects the overall dynamics. Thus, it is desirable that the measurement device mimics the dynamic behavior of an interacting human finger to imitate human-like interactions or in other words, to make sure that the captured interaction signals are able to characterize the dynamic behavior of a human-actuated control element around the operating point. If the actuation of the control element by the artificial robotic finger differs significantly from the human actuation, information about another operating point is captured, which might be irrelevant to the haptic perception of the control element.

To describe the dynamic behavior of human fingers a number of works identify the mechanical impedance parameters of fingers, most of them employ a linear second order system i.e. a mass-spring-damper system as the model structure (see [5] and [6]). In this work we also assume that the finger behavior can approximately be described by a mass-spring-damper system. The main principle of the proposed measurement approach is shown in Fig. 4(left): The finger mimicking probe is modeled as a mass-spring-damper system coupled with a model of the control element. The impedance parameters c_p, d_p, m_p represent the stiffness, damping, and mass of the probe. The interaction force $f(t)$ which is also the reaction force of the control element consists of the elastic force $c_s(x)x(t)$ and the force $f_d(\ddot{x}, \dot{x}, x)$ arising due to the dynamic properties of the control element. Note that the static measurement can only measure the non-linear stiffness

$c_s(x)$ depending on the displacement $x(t)$. The input of the coupled system is the probe movement $x_p(t)$. The equation of motion of this system is given by:

$$m_p\ddot{x}(t) + d_p(\dot{x}(t) - \dot{x}_p(t)) + c_p(x(t) - x_p(t)) = f(t) \tag{1}$$

$$f_d(\ddot{x}, \dot{x}, x) + c_s(x)x(t) = f(t). \tag{2}$$

During a measurement, a positioning system with the probe which is a passive mechanical mass-spring-damper system with a finger-like impedance pushes the control element with a typical pushing velocity of fingers[1] to reproduce human-like interactions and the interaction signals are measured.

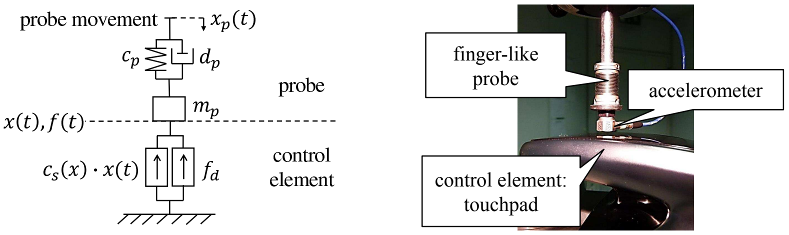

Fig. 4. Interaction model (left); Finger-like measurement device (right)

3.1 Measurement Device

To construct a mechanical mass-spring-damper system as the finger-like probe, the finger impedance parameters must be known. However, there are no finger parameters for a task such as pushing a control element available in literature. All finger parameters are identified under well controlled and specially designed experimental conditions e.g. special finger postures, finger movements or exciting signals. These conditions differ from the conditions of a manipulation task and are usually chosen to overcome the difficulty of identifying parameters in daily life tasks (see [6] and [7] for more details). Since these conditions have strong impact on the finger impedance, it is difficult to compare identification results obtained under different conditions and thus, impedance parameters of a particular task cannot directly be used for another task. In this work, the components of the probe are chosen in an iterative way and in each iteration it has been tested whether the probe can reproduce the human-like interaction. The resulting probe is shown in Fig. 4(right). It consists of a spring element and an accelerometer. The impedance parameters of this probe are identified and given by 1.8 N/mm (stiffness), 0.92 Ns/m (damping) and 6.6 g (effective mass). The reason of using an accelerometer instead of a force sensor is that a force sensor is usually too

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[1] To achieve the average pushing velocity, a pilot study with 5 subjects was carried out. It was observed that during the pushing and the subsequent releasing the finger moves with an almost constant velocity. The average velocity is 7 mm/s.

big and too heavy compared with a finger. Note that in (1), the interaction force $f(t)$ can be derived from acceleration $\ddot{x}(t)$ using integration, when the starting conditions, the movement and the impedance of the probe are known.

To validate this probe, the interaction between fingers and control elements and the interaction between the probe and the control elements are measured and compared: First, the probe pushes different control elements with 7 mm/s. Then, using the same accelerometer attached on the surface of the control elements, fingers of different subjects push the control elements with a repeated gesture and velocity profile. The acceleration is measured (accelerometer: PCB 352C65 with the bandwidth 0.5 - 10000 Hz; measurement duration: 200 ms; sampling frequency of the oscilloscope: 50 kHz). To quantitatively describe how accurately the probe can reproduce the finger interactions, a measure fit is defined by:

$$fit = (1 - \|\ddot{x} - \ddot{x}_f\| / \|\ddot{x}_f\|) \times 100\%,$$

where $\ddot{x}$ is the acceleration during pushing with the probe and $\ddot{x}_f$ is the average acceleration during pushing with the real finger. If fit approaches 100%, the probe can exactly reproduce the finger interactions. Three control elements: two touchpads and a push button were pushed by three subjects. The results show that the probe is a finger-like measurement device as it can reproduce similar interactions as fingers (9 fit-values of the probe for 3 control elements and 3 subjects are all greater than 70%: mean value 75.1%, standard deviation 3.44%). One of those results is given in Fig. 5. As a comparison, the dynamic measurements of the 2 touchpads with a rigid probe were also tested, these measurements differ significantly from the finger interaction (6 fit-values of the rigid probe for 2 touchpads and 3 subjects are negative: mean value -12.9%, standard deviation 4.15%), which indicates again that a finger-like probe is necessary to capture the dynamic behavior of control elements. If the rigid probe pushes that mechanical push button (without a active feedback force), the acceleration is equal to zero due to the constant pushing velocity (which means $fit = 0$).

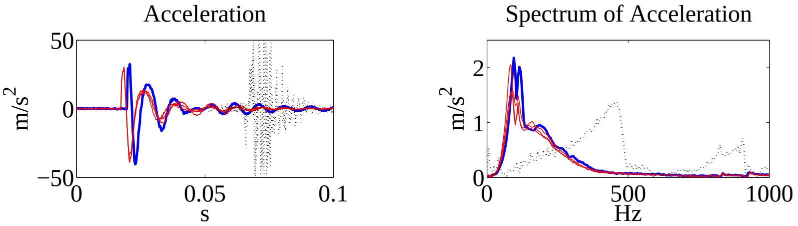

Fig. 5. Measurements of acceleration signals (left, in time domain; right, in frequency domain). The thin, red curves: accelerations when a finger pushes a touchpad; the thick, blue curve: acceleration when the finger-like probe pushes the touchpad; the black dotted curve: acceleration when a rigid probe pushes the touchpad. fit of the finger-like probe: 79.7%; fit of the rigid probe: -19.7%

3.2 Application Examples

In order to show the effectiveness of the new measurement method, acceleration signals during the snap of the push buttons and the touchpads mentioned in Section 2, see Fig. 2 and Fig. 3, are measured by the new finger-like probe pushing with the velocity of 7 mm/s.

The different haptic properties of the button with the additional mass is captured by the dynamic measurement method. As shown in Fig. 6, this button has smaller acceleration as large amounts of the signal energy is filtered out due to the mass. Thus, its snap feels dull and unclear.

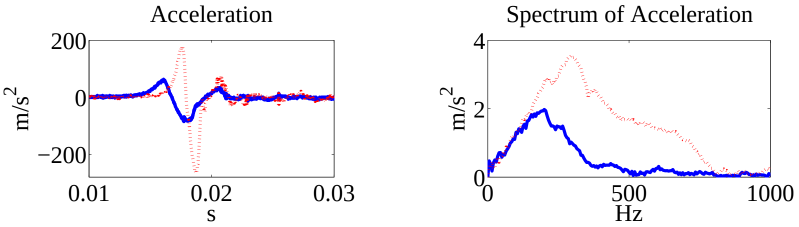

Fig. 6. Dynamic measurement of two push buttons with the same force-displacement curve, but different masses. Red dotted curve: basic push button; blue solid curve: push button with additional mass

The two touchpads with the same stiffness, but different active feedback forces differ significantly in the dynamic measurement, which is shown in Fig. 7. The touchpad sample I has a much larger acceleration and more signal energy and therefore, feels stronger.

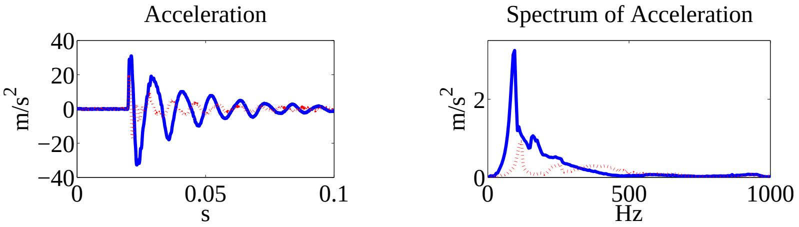

Fig. 7. Dynamic measurement of two same touchpads with different feedback forces. Blue solid curve: touchpad sample I; red dotted curve: touchpad sample II

Note that these control elements with different haptic impressions can not be distinguished by static measurements.

Using this finger-like measurement device we can capture the dynamic characteristics of a much larger variety of control elements without the need to take into account their mechanical structures and actuation concepts.

4 Discussion and Outlook

Using the newly introduced dynamic measurement method, control elements with same static properties, but still different percepts can be effectively measured for the first time. Instead of identifying the dynamic properties of control elements, the dynamic acceleration signal of the interaction between the measurement device and the control element is measured. The finger-like probe pushing with a typical velocity of fingers reproduces human-like interactions, so the measured signal corresponds to the dynamic behavior of the control element around the operating point of pushing with human fingers.

An important future work will target the derivation of features from the dynamic measurement and their correlation with subjective human impressions to establish a connection between subjective feelings and objective features. This connection can be used to specify the desired dynamic characteristic of the haptic feedback of control elements.

The probe of the dynamic measurement has so far constant impedance parameters, however, the finger impedance is much more complex than a mass-spring-damper system, it is highly adaptive due to muscle (co)-contraction and reflexes. Thus, the current probe cannot exactly reproduce the finger interactions. To further develop the measurement device to achieve a more accurate interaction, future work will also target the identification of the finger impedance during pushing and its control by an actuated robotic finger.

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