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## Abstract

The "feel" of a switch depends not only on the dynamics of the switch itself, but also on the motion and the dynamics of the human hand that actuates it. We have measured dynamic quantities during human actuation of a switch. We present a graphical technique called the "haptic profile" which emphasizes aspects of the feel of a switch as it is actuated by a hand, while minimizing the variability due to human actuation.

When designing new switches, it is important to have the ability to specify, measure, and verify the haptic properties of a switch. In order to do so, quantitative measures are required; qualitative descriptors of the haptic experience are insufficient. In this paper, we discuss the motivation and an apparatus for collecting the necessary haptic data.

#### 1. Introduction and Background

To put this research in context, a typical development process for a console switch at an automotive company (OEM) is illustrated. This process usually starts with a jury of designers/engineers selecting a Best-In-Class switch (BIC) from internal and competitors units. A supplier engineers a new switch using a sample of the BIC switch as a template, and a prototype is sent back to the OEM. However, the prototype switch rarely feels like the selected BIC sample. The challenge is that there are no quantitative metrics yet to characterize switch-feel, and as such, no complete description to be given to suppliers and no method to verify their final product. In an ideal process design requirements for switch-feel are quantitative and verifiable metrics based on psychophysical data. To determine these metrics, as well as to verify the produced switch, an accurate system to characterize the physical properties of existing switches is needed

Previous work with a device measuring force and position provided an incomplete haptic picture [1], so we designed a new device to more fully capture the haptic properties. Force, position, and acceleration were measured directly, as well as sound and electrical continuity information.

To capture the haptics of actual switches in situ, the measurement system is not mechanically driven; it is human actuated. This results in appropriate magnitudes for real-life forces, velocities, and accelerations. Due to the human element, the measured data varies considerably from cycle to cycle. Plotting the data using standard signal versus time techniques proved difficult to interpret. Instead, we plot several measured variables against each other to create a "haptic profile." The haptic profile emphasizes features of the data that seem to correlate with the human perception of the switch's "feel".

There is some related research in this area developing methods to characterize the haptic properties of devices. [3] developed a characterization technique known as the "Haptic Camera" to measure and characterize the feel of a toggle switch. This method involves a mechanically actuated measurement system, as opposed to our work which is a human-actuated system. The haptic camera system then applies an assumed model of switch behavior to small, continuous sections of the resulting data to identify the mass, damping, stiffness, and model parameters.

Other related research [4] presents a technique using a wavelet network to characterize nonlinear haptic environments.

We tested three different linear switches, shown in Figure 1. Typical descriptors for these switches are "clicky," "smooth," and "mushy," words which give a sense of the highly qualitative state of the art in switch characterization. The names are more for distinguishing

one from another than they are an accurate description of the switch-feel. The clicky switch has two stable states, similar to a ballpoint pen. The smooth switch is exactly that, a smooth momentary switch, with no intentional features other than the solid feel. The mushy switch is a momentary type with a discernable detent or "over travel" feel.



Figure 1. Picture of switches measured

# 2. Apparatus

We designed a device to measure the haptic properties of linear switches as they are actuated by a human hand. We measured force, position, acceleration, sound, and electrical continuity data. Velocity information can be derived from both the position and acceleration signals. The goal of the device is a haptically transparent recording system. While it is not possible to make a completely transparent measurement system, the device was designed with low inertia and as little friction as possible in the moving parts of the system.

The device is mounted on the end of a rectangular beam mounted so that it is rigid against gravity, but flexible along the axis of switch travel. See Figure 2. One end is fixed, while the free end of the beam is outfitted with sensors. All of the actuation forces on the switch pass through a 3/8 inch diameter load cell. An accelerometer measures the acceleration of the switch along the direction of switch travel. Position sensing is accomplished by imaging an LED (mounted on the end of the beam) onto a lateral effect photodiode which is fixed 50cm away. A microphone situated close to the back of the switch measures sound information. Electrical continuity of the switch is also measured.

We used a computer equipped with the QNX real-time operating system and a Servo-To-Go Corp. interface board for data acquisition. The data acquisition was accomplished using custom software measuring and recording the sensor outputs at 2Khz.



Figure 2. Top view of experimental apparatus in two switch states

# 3. Data Display

The goal of this research is to collect haptic data and display it in a useful and intuitive manner. As will be discussed, one of the typical methods for plotting data, signal versus time, is useful, but probably not an ideal technique for displaying the haptic information collected for a switch. Plotting the data using time independent axes provides a much more intuitive picture of the feeling of a switch. We first discuss signal versus time plotting, and then discuss plotting the data using a technique that results in what we call the haptic profile.

### 3.1. Chronological plots

Figure 3 is a typical chronological plot displaying position, force, and acceleration data from the clicky switch. One can clearly see the brief spike in acceleration as a switch initially starts to move during an actuation cycle. Looking at the position curve on the plot, the two stable states are indicated by a constant position of 0 mm for the "off" state and a position of 2.7 mm for the "on" state. When the position reaches a maximum, the force rapidly increases; this corresponds to the user reaching the maximum travel and feeling the switch "bottom out." It is likely that the momentum in the user's hand and arm induces this rapid increase in force as the finger begins to compress against the front of the measurement device before the person can react to stop pushing.

# 3.2. Haptic Profile

We began to interpret and compare the behavior and haptic properties of different switches using chronological plots, such as in figures 3 and 4. Clearly, the data contains observable differences between switches; it is difficult to intuitively interpret aspects of the "feeling" of a switch using such a plot. One problem is that the speed of actuation differs from trial to trial and from user to user.







Figure 4. Chronological data for smooth switch

Another problem is the difficulty of feature identification. Identifying small changes in slope over time, or other salient haptic features, is difficult without more sophisticated analysis. Differences in signal magnitudes are evident, but it is not readily apparent how the feeling of two switches differs by looking at a chronological plot. A more intuitive data presentation technique would be a much better solution, which led us to what we call the "haptic profile."

One of the primary criteria in developing an alternative method to display haptic data was to reduce the apparent time dependence of the data. Plotting the data using axes that do not directly depend on time makes data from different switches easier to compare, since the axis ranges can be equalized. Instead of plotting the information versus time, we plot the haptic data against itself using a three-dimensional technique. Mathworks Matlab analysis software provides powerful built-in tools for creating and manipulating three-dimensional plots, and their twodimensional representations. Figure 5 shows the result, a single line in space that represents the haptic properties of a switch. (Although it is a single line, it overlaps itself on repeated, similar actuations.) This emphasizes the attributes of the switch, instead of emphasizing the timing of the actuation process, such as with chronological plots. We chose force, position, and velocity as the three principle axes of the haptic profile.



Figure 5. Isometric view of haptic profile for clicky switch

Plotting all of the experimental data was not ideal, due to the quantity of data present, and the noise present in the signals. These factors broadened the lines and had the effect of washing out or covering up most of the subtle features. To create a more useful illustration, we filtered the data using a time-based windowing technique.

A time-based window is advantageous for the following reasons; first, by averaging the data inside each window, the number of points is reduced. Second, the averaging window low-pass filters the data to reduce the noise present in the signals. The result is a plot that appears very different from the chronological plots previously shown, however it becomes much easier to interpret. Like a mechanical drawing, four views can be used to identify the haptic profile, an isometric or angled view, in addition to three orthographic projections. Each projection removes one of the axes and reduces the three-dimensional plot to two-dimensional. The angled view is more useful for qualitative purposes, because the viewing angle makes it hard to interpret and typically obscures part of the data.



Figure 6. Force-position projection of haptic profile for clicky switch



Figure 7. Position-velocity projection of haptic profile for clicky switch

Projecting the haptic profile onto the position-velocity projection allows one to see the two stable states of the clicky switch, as illustrated in Figure 7. The top half of the large outer loop and the bottom half of the smaller inner loop comprise the first half of an actuation cycle, going from the stable off state to the stable on state. The second half of the actuation cycle is composed of the top half of the inner loop and the bottom half of the outer loop. Positive velocities, defined as increasing switch compression, are above the horizontal axis, while negative velocities lie below the axis.



Figure 8. Force-velocity projection of haptic profile for clicky switch

Since the haptic profile is generated using data collected from a human-actuated switch, some variability and noise is to be expected. An important feature to note is the cyclic nature of the haptic profile. Since the switch always returns to its nominal resting state, the path of the haptic profile always takes the form of a loop. The arrow indicates the direction of travel around the loop.

Using force, position, and velocity for the axes does not directly incorporate the acceleration information. To add this extra information to the haptic profile without excessively increasing the complexity, we change the color of the line at each point to reflect the high frequency acceleration, or vibration, at that point. The low frequency components of the acceleration at a particular point on the haptic profile are already represented through the slope, and change in slope, when viewed on the position-velocity projection, so the missing information is the high frequency components of the acceleration signal. To display these, the acceleration signal is high-pass filtered and then the RMS (root mean square) value of the filtered acceleration over that window is converted into a color value to represent to overall quantity of vibration at each point on the haptic profile.

Vibration, represented by color, is translated into a percentage of the maximum observed high frequency acceleration for any of the switches. This means that a dark red color, corresponding to 100, would be a high

frequency acceleration RMS value of 100% of the maximum observed for the three switches; the clicky switch exhibited the largest high frequency signal, setting the overall scale. Similarly, a dark blue color, corresponding to 0, would correspond to no vibration at that point on the haptic profile. This allows direct comparison between haptic profiles for different switches, since the color scale is universal.



Figure 9. Force-position projection of haptic profile for smooth switch



# Figure 10. Position-velocity projection of haptic profile for smooth switch



Figure 11. Force-velocity projection of haptic profile for smooth switch



# Figure 12. Force-position projection of haptic profile for mushy switch

There is some amount of "tuning," by adjusting the filter window length, to maximize the utility of the haptic profile. We found that using a smaller window in time to plot the position, force, and velocity information, while using a longer window for the acceleration measurements is advantageous for calculating meaningful acceleration RMS values. [5]

The small magenta circles on the haptic profile indicate a change in electrical continuity. On the force-position projection of the haptic profile, when traveling from the origin to the point of maximum depression, the magenta circle indicates when the switch turns on. The magenta asterisks indicate an impulsive, or clicky, sound. These two markers can be used to investigate any correlation (not necessarily causality) between clicks or changes in continuity and possible haptically perceptible information, such as a change in slope of the haptic profile on the force-position projection

Additionally, since the haptic profile is inherently three-dimensional, short movie clips of the three haptic profiles rotating in space to illustrate all of the views can be downloaded here:

# http://lims.mech.northwestern.edu/students/weir/2004hapti cssymp/

Full-color haptic profiles of the three switches can also be downloaded from the same location.

## 3.3. Properties of the Haptic Profile

The haptic profile highlights many features of the switch that would otherwise be difficult to observe, and at the same time masks much of the time dependent variability between actuations. The switches we measured do not have significant viscous friction, the majority of the friction is Coulombic, so the force-position projection displays most of the fundamental switch behavior. Switches that have more viscous friction would exhibit a broader spread in the haptic profile on the force-position projection, since the actuation force would increase with increasing actuation speed. Since all of the loops in the haptic profile on the force-position projection line up well and mostly reduce to a single line, this indicates that the force required to compress the switch a given distance is independent of the velocity at which it is actuated. This is a characteristic of Coulomb friction, a good example of which is the hysteresis observed in Figure 9.

The haptic profile of the smooth switch looks very different and one would intuitively guess that it feels different. The clicky switch has also been described as "scratchy," which may be an indication of the wiggles in the haptic profile on the position-velocity projection. Unlike the clicky switch, the smooth switch does not exhibit these wiggles, and not surprisingly feels "smoother," as shown in Figure 10. Interestingly, the feature on the force-position projection for the smooth switch, shown in Figure 9 at a displacement of approximately 1.75 mm, feels like a flaw in the mold, or a small, unintentional catching point as the switch is depressed. These types of features are very difficult to find and identify on the chronological plots, however they

stand out clearly on the haptic profile. The horizontal sections near the origin, when starting a loop, are an indication of the internal spring preload or force threshold that must be exceeded before the switch begins to compress. The same effect can be seen on the chronological plots by an apparent delay between the start of the force curve and a change in the position signal, although it can be very subtle. The linear relation between force and displacement is also evident for the majority of switch travel, except for the threshold at the beginning and the solid stop at the end of travel.

When analyzing the mushy switch in figures 12 through 14, a detent is visible both on the force-position projection and also on the force-velocity projection. Since the force decreases rapidly as the displacement reaches the detent, the user feels his finger pulled into the detent. There is actually no attractive force, since the force remains positive, but the inertia of the users hand and arm and the delays present in the nervous system likely prevent a person from stopping on the decreasing side of the curve. This is also shown as the upward curving path on the force-velocity plot for the mushy switch.



Figure 13. Position-velocity projection of haptic profile for mushy switch



Figure 14. Force-velocity projection of haptic profile for mushy switch

### 4. Interpretation

Just by looking at the curve many anecdotal comments come to mind. For example, wiggles in the positionvelocity projection of the haptic profile will correspond to a certain degree of undesirable roughness, or in other words, a scratchy feel. The two switch samples described in this paper show a somewhat linear relationship between position and force, and as such, they can be assumed to feel somewhat like a spring. Additionally, the separation between sections of curves in the loop provides useful information about the amount of friction present in the switch, and the color code of the haptic profile is a sort of frequency signature.

However, this is just the starting point. There are some basic questions that need to be answered. One is, what features and variation on the haptic profile can be perceived? Second, what are the features / characteristics in the haptic profile that are dominant i.e. have the major impact in differentiating the switch-feel? Third, what combination of features results in a pleasant feel?

Answering these questions requires an exhaustive set of human factor studies, where specific parameters of switch-feel are controlled by using a switch simulator, i.e. a dedicated haptic device. Some of these studies are already under way at Ford [2], and as a joint collaboration with Purdue University to investigate rotary switch-feel [6]

The end result will be the much needed metrics for designing switch-feel and a process to provide quantitative targets and tolerance to switch manufacturers.

In this context the measuring device plays a central role. First, different samples built using existing technologies need to be measured to identify the currently achievable design space for various type of switch actuation. This will help narrow the range of variation to be investigated during human factor studies. Second, the measuring device can be used to verify that the switch simulation device can indeed replicate the desired physical feel. An existing switch could be measured and its characteristics imported into a model rendered by the playback system. The haptic profile of the playback system could then be measured and checked against that of the real switch. Third, once the metrics are in place, the measurement device will become a standard quality control tool

#### 5. Conclusions and Future Work

We designed and built a switch measurement device that measures many of the haptic properties of pushbutton switches. To complement the measurement device, we developed the haptic profile to effectively display the resulting haptic data.

The present form of the haptic profile has benefits and also disadvantages. No time information is directly plotted, making it difficult to isolate when and for how long a user may experience a particular feature. However, time points can be added to the haptic profile. Time points are useful for illustrating how some sections are covered in a very short period of time, while in other areas of the haptic profile the switch is moving rather slowly.

Another disadvantage of the haptic profile is that when many loops are displayed, the data tends to overlap itself, making it difficult to identify a particular actuation. One easy way to get around this is to only plot a few actuation cycles in the haptic profile.

Overall, the measurement system works, and the haptic profile seems to be a good method of displaying some of the data in an intuitive manner.

In the future, a number of incremental improvements can be made to the measurement device to improve its performance. A very stiff and light rigid rod with a rotational joint at the fixed end, instead a flexible bending beam, would greatly limit the off-axis movement and torsional compliance of the system. It would also simplify a detailed analysis of the inertial effects of the measurement device.

We have begun work on designing and building a high mechanical bandwidth, linear haptic display to work in conjunction with the measurement system and mathematical models of the switch. As mentioned in the previous section, this will provide a means of feeling and measuring the effect of changing a particular parameter or aspect of the haptic profile. To identify and characterize specific feelings requires human factor studies and a method to calibrate the system with the resulting data.

To further complement the work at Ford and Purdue, Northwestern plans to join in analyzing the psychophysical aspects of switch-feel. Both the measurement system and a linear haptic display should prove to be useful tools for such a study.

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