# One Button to Rule Them All: Rendering Arbitrary Force-Displacement Curves

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## ABSTRACT
Physical buttons provide rich force characteristics during the travel range, which are commonly described in the form of *force-displacement curves*. These force characteristics play an important role in the users' experiences while pressing a button. However, due to lack of proper tools to dynamically render various force-displacement curves, little literature has tried iterative button design improvement. This paper presents *Button Simulator*, a low-cost 3D printed physical button capable of displaying any force-displacement curves, with limited average error offset around .034 N. By reading the force-displacement curves of existing push-buttons, we can easily replicate the force characteristics from any buttons onto our Button Simulator. One can even go beyond existing buttons and design non-existent ones as the form of arbitrary force-displacement curves; then use Button Simulator to render the sensation. This project will be open-sourced and the implementation details will be released. Our system can be a useful tool for future researchers, designers, and makers to investigate rich and dynamic button's force design.

## INTRODUCTION
A physical button is a transducer that registers the motion of a finger, changes the state of a machine, and returns to resting state [3, 5, 7]. One important property that a physical button provides is the rich force feedback throughout its full travel range, and such characteristics are commonly represented as the force-displacement curves (see Figure 2 as an example). Every button has its own curve, which can be quite different from each other and further lead to various user' experiences [1]. For this reason, most button manufactures provide force-displacement curves in their datasheets.

However, there has been surprisingly little research tried to investigate proper design and engineering of buttons' force-displacement curves. One reason leads to the problem is that these haptic properties are determined by its mechanical structure when it's manufactured. Comparing to virtual buttons in GUI, whose layout [6] and even corresponded vibrotactile feedback [4] can be easily adjusted by program, the physical buttons provide little space for exploring various force-displacement curves. Without a proper device to dynamically render such force-displacement characteristics, designers and researchers have no choice but to exhaustively examine a set of commercial buttons.



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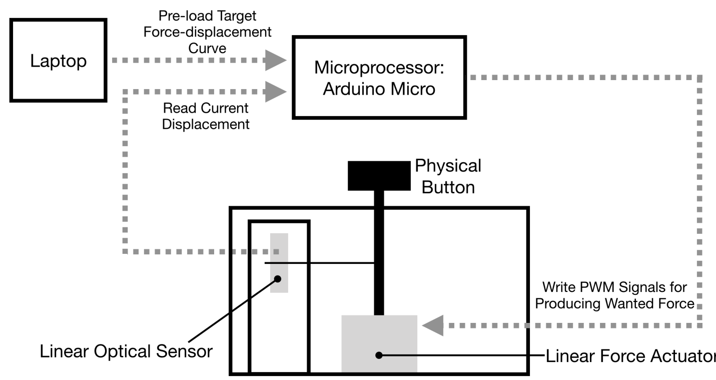


**Figure 1. The Button Simulator system.**

One notable exception was Doerrer's key-simulator [2] back in 2002, which proposed a push-button that generates programmable resistance force. With such machine, Doerrer studied the user preferences of basic force-displacement curves. However, there are several limitations that constrain Doerrer's work to be replicated by others: First, implementing details were not fully presented, and the hardware and software are not available nor affordable for normal makers. Second, the technical evaluation of the system was lacking. Lastly, it only simulated force-displacement curves with very simple, which didn't bridge the force-displacement curves of actual existing buttons.

To fill in the aforementioned technical gap, we present *Button Simulator* (Figure 1 and 3a), a 3D printed system that renders force-displacement curves. Different to Doerrer's work, Button Simulator is low-cost, open-sourced, and easy to construct. Most importantly, it can replicate any arbitrary curves, which provides much richer options than previous work. These force-displacement curves can easily be obtained by commer-

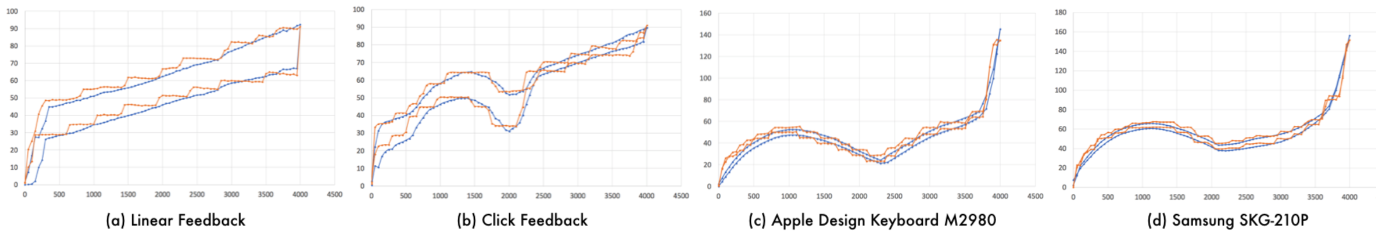


**Figure 2. Four buttons rendered by Button Simulator: the blue lines represent the original force-displacement curves while the red lines represent the ones made by the our system. The units for x and y vectors are micrometer and centinewton for all the four plots.**

cial datasheets directly, or measuring button with equipment[1] or manually created. The 3D models and codes of Button Simulator will be released online and the required electronics cost only around 350 dollars. The main contribution of our work is making this system available for future makers, designers and researchers to explore the force design of buttons.

## BUTTON SIMULATOR SYSTEM

Button Simulator (Figure 3a) is a push-button with the ability to freely change force feedback within its travel range. That means it is possible to configure the force exerted by the button depending on the displacement of the key position. As depicted in Figure 1, the system is built on a microprocessor (Arduino Micro), which connects with a linear optical sensor (TSL1401 Linescan) and a linear force actuator (Moticont LVCM-025-022-01). The sensor is constantly detecting the precise displacement of the button and sending the data to the microprocessor. Which will determine the needed force based on the displacement and the pre-loaded force-displacement curve, and further calculate the PWM signal to the motor to generate corresponding upward force. The Button Simulator takes comma-separated values (csv) files as simulating force-displacement data beforehand, which contains one column of displacements and another column of corresponding forces. The travel range is adjustable and up to 6 mm.

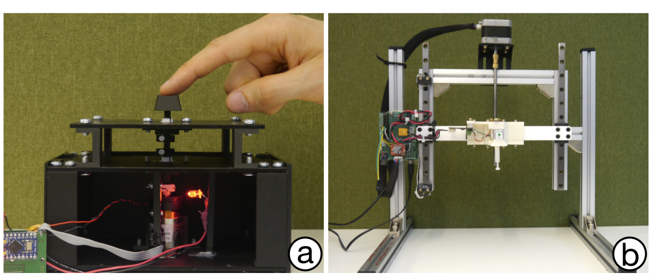


**Figure 3. (a) The picture of Button Simulator. (b) Self-made force-displacement measuring machine.**

Since it's a time-critical task, the responding rate of the sensor and the actuator have been boosted. An LED light is placed close to the optical sensor to minimize the exposure time. We also manually alter the signal output rate of the Arduino board to minimize the motor responding time.

[1]http://www.forcegauge.net/en/category/force-displacement-en

## TECHNICAL EVALUATION

To validate the performance of the Button Simulator, we rendered the force-displacement curves of four actual buttons: a linear feedback button, a click-feedback button, and two commercial keyboards (Apple M2980 and Samsung SKG-210P). As shown in Figure 3b, a self-made force-displacement measuring tool with the resolution of 20 data points per millimeter (one data point per 50 $\mu$m) is used for gathering the data for simulation. Then, we rendered force-displacement curves of each button five times and use the identical measuring equipment to measure the results with identical resolution. The average error offsets are .0338 N, .0259 N, .041 N and .0338 N for linear button, click button, Apple M2980 and Samsung SKG-210P respectively, which makes .0336 N error in total average.

One limitation found in the experiments is the step-like generated force, that was due to the limited DAC resolution of the microprocessor (8-bit bandwidth). This can be easily mitigated with a microprocessor with higher DAC resolution. The other observable limitation is that linear actuator can not stably create relatively weak force (<.2 N). However, the differences under such weak force are nearly non-detectable by human and lead to limited subjective differences. The last limitation, which is not revealed in the quantitative results, is that the delivered sensation might not be realistic if the button is pressed too fast. This issue is raised by the limited scan rate of the linear camera (430 Hz). The problem can also be fixed by switching to a higher speed camera or position sensor.

## DISCUSSION AND FUTURE WORK

In the future, except for the improvement mentioned in the aforementioned section, we will also extend the work in following directions. First, innovative haptic design: The force generated in the system currently is only displacement-dependent, but we can explore much more possibilities. For example, simulating a velocitydependent force button, such as non-Newton fluid[2]: the faster you press, the stronger resisting force encountered. We can also make a multi-state button, that means the button contains more than one states, and each of the states has its own unique force-displacement curve. Second, open-sourcing the project: All the 3D models, program, instructions for setting up the system, and collected force-displacement curves will be released online. The system can be useful for designers and researchers to conduct force-pressing experiments, improving the haptic design of physical buttons.

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[2]https://en.wikipedia.org/wiki/Non-Newtonian_fluid