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Endless knob with programmable resistive force feedback

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Abstract. Touchscreens today represent the most versatile solution for configuring user interfaces. A toll for this versatility is the intangibility of the displayed virtual controls. The addition of haptic feedback can improve their manipulation by reinforcing or even substituting visual information. While haptic rendering of virtual buttons is advancing, tangible knobs seem yet to come, possibly due to the inherent difficulty to conceptualize rotation as an interaction primitive in absence of a physical control. To address this issue, we propose a hybrid solution consisting in an endless knob with programmable resistance to rotation. Compared to existing related devices, it minimizes costs, encumbrance and power consumption, making its installation also possible on portable equipment. After describing its design and main features, we present a test which assessed how haptic feedback rendered by the knob affects performance in a visual target-matching task: users had to select targets placed on a horizontal slider by dragging its cursor through knob rotation. Results show that haptic augmentation significantly improved target acquisition.

1 Introduction

In the last decades, interaction with machines has undergone radical changes. In spite of a long-established design tradition of their physical layouts, typical controls such as buttons, switches and knobs have often been replaced by virtual counterparts finding place on touchscreens and capacitive surfaces. Whenever direct manipulation provides safer and simpler interactions, however, tangible controls are still preferred. In today's cars, for instance, most auxiliary functions are accessible from touchscreens, whereas those which more closely affect driving are still a domain of physical knobs and selectors [18]. Tangible controls in fact provide rich haptic feedback allowing safe eyes-free selection while performing other main tasks such as driving [23]. Furthermore, by distributing part of the cognitive load onto the somatosensory channel, they ensure control accuracy in several everyday contexts and work environments [16].

Even if eyes-free interaction can be partially enabled on touchscreens through advanced vibrotactile feedback [21], electroadhesion [26] and friction modulation [28], on the other hand such augmentations do not guarantee more efficient interactions. For instance, no significant effect on performance was found using

touchscreens with vibrotactile feedback under demanding conditions (e.g., when dialing a telephone number while driving a car) [16].

In between virtual and physical layouts, tangible digital controls can be provided with variable haptic feedback: programmable buttons [17] and sliders [4] can render different force/displacement curves, whereas haptic knobs can generate multiple effects such as detents, barriers, spring repulsion through variable torque (see Sec. 2). The main downside of devices offering force feedback usually reside in their size, power requirements, and cost which may be several orders of magnitude higher than that of their purely mechanical counterparts. For instance, a mechanical detented knob can cost less than 1 USD, whereas a programmable haptic knob may easily be 100 times as expensive (e.g. [2,6]); moreover, a haptic knob requires electrical power and is usually much larger. These drawbacks typically limit the use of such haptic devices to expensive or safety-critical control panels [29] and to the research laboratory [14].

Here we propose a low-cost, compact knob with programmable resistive force, built around an electromagnetic braking system. Because of the absence of a motor and other active components, power consumption is much lower than that required by similar existing products. The effectiveness of the implemented resistive force effect was tested in a visual target-matching task operated using the knob with or without feedback: the former resulted in higher accuracy and shorter execution time.

2 Related work

Different studies focusing on the manual control of visual tasks, occurring especially during machine operation, have found that the inclusion of context-dependent haptic feedback can improve human performance, particularly when the cognitive load is high and multiple tasks are performed at the same time [24,7,16].

For instance, experiments comparing physical and virtual knobs have shown that tangibility has positive effects on several interaction efficiency measures [30,23]. More in detail, physical knobs decrease error rate and speed up task completion up to 20% as compared to their virtual counterparts. Mainly for this reason, some recent smart gadgets incorporate or offer additional physical knobs: examples include Google Nest [11], an intelligent touchscreen-based thermostat, and the remote multimedia controllers Griffin PowerMate [12] and Microsoft Surface Dial [19].

These evidences suggest that the tangibility of physical knobs is still appealing. At the same time, today it would be desirable to expand their flexibility towards multi-parametric control as currently offered by virtual knobs, which, on the other hand, cannot be operated when visual attention is focused elsewhere (e.g., during teleoperation) [22,7].

One way to make the manipulation of multiple quantities through a single physical knob more intuitive is to provide it with haptic effects simulating various mechanics. However, this comes at the cost of embedding actuators and their

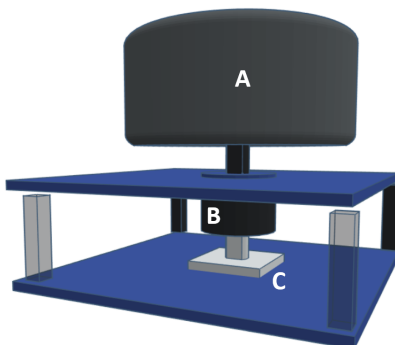


Fig. 1: Schematic of the haptic knob: the end effector (A) is connected to an encoder (C) by means of an electromagnetic braking system (B).

relative electronics in the knob, adding cost, complexity, encumbrance and power consumption. As a result, force-feedback rotary controllers are found only where this can be tolerated: car dashboards, piloting systems, professional audio/video editors, robot controls and medical devices. Most such controllers make use of DC motors to generate force feedback [3,25,13]. Hybrid solutions that combine motors and brakes have been proposed as well [6]: while allowing the design of subtle effects, they further increase hardware complexity. Even more expensive and technologically advanced solutions make use of magneto-rheological fluids in which the knob shaft is immersed [29,2]: in this case, magnetic-field variations are used to change the density of such fluids, allowing precise control of the resistive torque.

Finally, programmable haptic feedback is going beyond the mere reproduction of mechanical features like torque and detents, as the idea of branding machine interfaces with a unique haptic “feel” is progressively finding a relevant place in current technology trends [27,14,5,25]. In synergy with rigorous functional design constraints, this idea has nurtured controllers such as the jog wheel aboard the recent Traktor Kontrol S4 DJ console [20]. With this design scenario in mind, we have prototyped an endless knob with programmable resistive force feedback, which is described in what follows.

3 Hardware / software design

Our knob can be programmed to generate frictional patterns which, by resisting against rotation, induce resistive force-feedback effects. Its main hardware components consist of a rotary encoder coupled with an electromagnetic braking system that is controlled by an Arduino microcontroller through its pulse-width modulation (PWM) output. The details of the hardware have been filed in view

of patenting the technology [9], whereas its application as a multimedia production controller has been presented in [10]

Compared to existing haptic knobs, the proposed electromagnetic braking system has advantages and drawbacks. The main advantage is that it can easily couple a standard knob to an encoder (see Fig. 1), resulting in a thin, lightweight and low-cost device. It also needs less power than DC motors [3], hence enabling battery-supplied portable solutions. The main shortcoming is lack of active force, which limits the feedback to changes in torque, and reproduction of detents as well as end-stops. The implemented control algorithm samples the encoder position and estimates its rotation speed during unidirectional shifts; these data are then used to set the magnitude and duration of the resistive force. The current prototype mounts a magnetic encoder with a resolution of 4096 points per revolution, that is, less than 0.1 degrees.

The output voltage of the microcontroller (between 0 and V_{CC}) depends on the relative length of the PWM duty cycle, and directly controls the resistive torque of the knob. For example, if the output maintains a constant voltage, then a proportionally constant torque is applied against rotation.

Detents are reproduced as follows: once the encoder detects the position occupied by a detent, the algorithm sets the length of the PWM duty cycle and the value of a counter, depending on the programmed resistance and estimated rotation speed. The counter is decremented at every cycle, and the electromagnetic system operates at a constant PWM value until the counter reaches zero. The harder the detent, the longer the knob resists against motion.

Fig. 2a shows the temporal evolution of the mentioned variables for two different haptic effects: in the first event (E1), a soft detent is simulated by applying the highest possible resistance for 50 ms; in the second (E2), the action of the braking system is modulated with short activations so as to generate a lower resistance, slowing down hand movement however without stopping it.

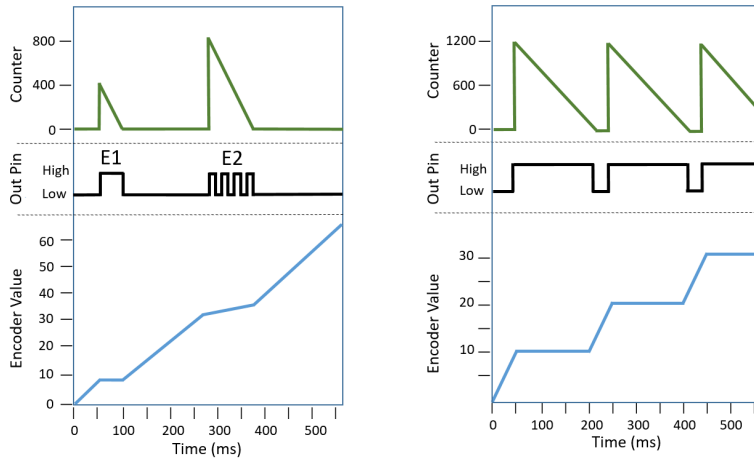
In addition to rotation, the knob can also be pushed as a button. Overall, six different input modes are made available by combining clockwise and counterclockwise rotation with no, short or long push.

4 Evaluation

A visual target-matching task was set up to test the effect of resistive feedback while performing an action that was functionally equivalent to a drag-and-drop action.

4.1 Procedure

Participants were asked to sit at a desk where a computer screen, keyboard and the knob were placed. The screen displayed a GUI developed in Processing 3.5 (see Fig. 3): using the knob, a red vertical segment representing a cursor could be dragged horizontally along a virtual slider which contained five equally spaced round markers. Two buttons completed the GUI, labeled ‘Confirm’ and ‘Reload’:



(a) Two example effects: E1 simulates a soft detent by setting the PWM duty cycle to 100% for 50 ms, resulting in a brief rotation stop; E2 simulates a lower constant resistance by repeating several PWM duty cycles at 50%. (b) Hard detent effect, repeated every ten encoder steps. Hard detents are simulated by almost stopping hand movement. This is achieved by setting the PWM duty cycle to 100% for 150 ms, resulting in a strong resistive force.

Fig. 2: Temporal evolution of control variables for various haptic effects: when the encoder position (blue line) reaches a predefined value, resistive force is generated by activating the output signal (black line) until the counter (green line) is decremented to zero. The generated resistive force is proportional to the length of the PWM duty cycle.

they were operated by the computer keyboard respectively for confirming that a target was successfully matched, thus ending the trial, or for repeating the current trial.

The shift of the cursor had an accuracy equal to 11.4 pixels per degree of rotation; the markers were set 320 pixels apart from each other, corresponding to a rotation by about 28 degrees.

At the beginning of each trial, the cursor was reset to the position marked with ‘Home’ in Fig. 3, and one of the markers along the slider was surrounded by a red circle, symbolizing the current target. Participants had to select this target by dragging the cursor over it: in order to move the cursor they had to push down the knob and turn it. When they reached the target, they released the knob and chose whether confirming or repeating the trial by pressing the respective button on the keyboard using the other hand. At each trial, haptic feedback was either present or absent; when present, it reproduced a hard detent (see Fig. 2b) in correspondence of a marker. Each factor combination of 5 targets



Fig. 3: The GUI used in the experiment. A vertical red cursor is controlled by the haptic knob; it moves along a virtual horizontal slider which hosts five round markers. At each trial, one marker is highlighted with the red color, thus becoming the current target. The blue squares are activated by pressing the corresponding buttons on the computer keyboard.

$\times 2$ feedback conditions was repeated 10 times, hence resulting in 100 trials which were randomly balanced for each participant.

A repetition was typically invoked when participants released the knob off-target, similarly to what happens when a wrong drag-and-drop action made with the mouse must be undone. If a trial was confirmed, then the time elapsed from the knob initial press to its release was measured, along with the distance of the cursor from the target (called mismatch from now on).

Ten participants (7 males, 3 females) aged between 24 and 57 ($M = 39.9$, $SD = 10.3$), all right-handed, took part in the test on a voluntary basis and were not paid. Before the test, participants performed a training session consisting of 10 trials, in which each factor combination was presented once in random order.

4.2 Results

Fig. 4 and 5 respectively show box plots of the mismatch in pixel and time-to-match in ms, for each factor combination. Tests on the data distributions with the D’Agostino method [8] confirmed no significant deviation from normality.

A two-way ANOVA was conducted to study the influence of the two independent variables (target position, feedback condition) on mismatch. Using a Greenhouse-Geisser correction for insphericity, the main effect for feedback yielded $F(1,9) = 13.4$, $p < .005$, indicating a significant difference between trials in presence of haptic feedback ($M = 3.7$, $SD = 0.31$) and without it ($M = 4.54$, $SD = 0.31$). The main effect for position instead was not significant with $F(1.5,13.6) = 0.2$, $p > .05$, and so was the interaction effect: $F(2.5,22.5) = 2$, $p > .05$. In agreement with previous studies [24], our results

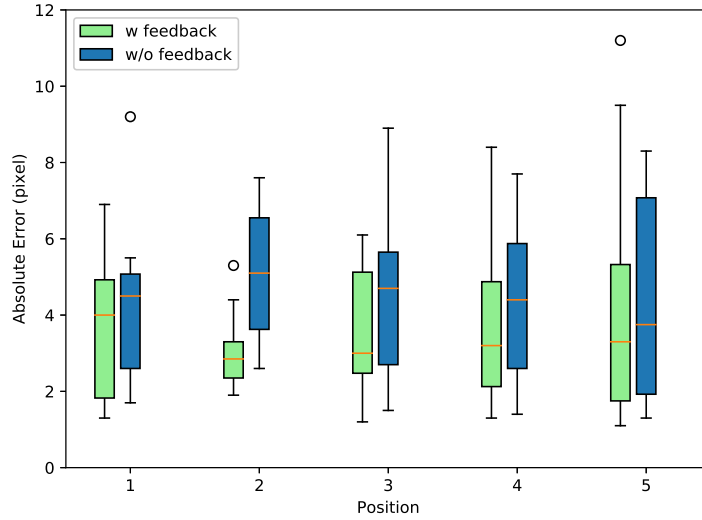


Fig. 4: Box plots showing the mismatch for each factor combination.

show that haptic feedback significantly improved the precision of the action. The smaller mismatch did not come unexpected though, as the increased resistance to rotation occurring while traversing a marker supported participants to stop the cursor at the right location. A further two-way ANOVA was performed to study the influence of the two independent variables on the time-to-match. After a Greenhouse-Geisser correction for insphericity, the main effect for feedback was not significant with $F(1, 9) = 0.43$, $p > .05$. The main effect for position yielded $F(1.4, 12.8) = 22.3$, $p < .001$, indicating a significant difference between position 1 ($M = 1396$, $SD = 150$), position 2 ($M = 1720$, $SD = 145$), position 3 ($M = 1799$, $SD = 133$), position 4 ($M = 2049$, $SD = 184$) and position 5 ($M = 2223$, $SD = 170$). The interaction effect was not significant: $F(1.5, 13.3) = 1.4$, $p > .05$. The time-to-match depended on the position, with longer time associated to farther targets. While this result may appear obvious at first, one must consider that haptic feedback caused resistance to knob rotation each time a marker had to be traversed, however this had no significant effect on time-to-match. Even further, the time-to-match in presence of haptic feedback was on average generally lower, suggesting that resistive force potentially enables even faster execution of target-matching tasks.

5 Conclusions

A low-cost knob controller with programmable resistive feedback was prototyped.

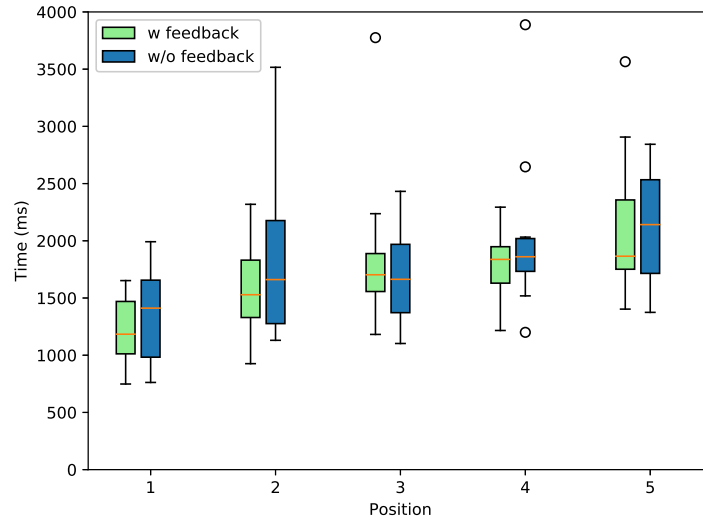


Fig. 5: Box plots showing the time-to-match for each factor combination.

Its effectiveness was assessed in a visual target-matching test that showed a significant reduction of the positional mismatch when resistive feedback was applied to the knob.

Our study suggests that, even in absence of active forces as those provided by more expensive, bulky and power hungry motorized knobs, resistive feedback has concrete potential to support effective visual browsing of sequential domains such as sliders, top-down menus, and in general all those maps where physical rotary controls can be conveniently employed for the selection of targets.

Future plans include the design of refined haptic effects and the development of a systematic software communication framework operating between the knob and applications able to send/receive control messages belonging to standard protocols.

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