Evaluation of rotation gestures in rotary vs. motionless knobs

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***Abstract*— In environments where knobs are frequently damaged by mechanical wear or seepage of liquids, the use of sealed substitutes without moving parts has been tested. In this case, users slide their fingers around a still cylinder rather than rotating a knob. A comparative experiment is reported in this paper, in which participants were asked to perform rotation gestures by specific angles on either a rotary or motionless knob, both hidden to sight. Concerning rotation performance, no significant differences were measured in terms of mean accuracy and precision; however, sliding caused larger deviations in the final position of the fingers. In parallel, a questionnaire unveiled issues of affordability of the motionless knob. Our experiment is preliminary to the realization and validation of a haptic rotation sensing technology applicable to graspable motionless cylinders.**

I. Introduction

Knob controllers are widely adopted in professional appliances since they can be grasped and operated even without visual feedback: for their unimodal character, such tasks are called *haptic rotations* in the human-machine interaction literature [1], as they involve only the somatosensory system in the perception-and-action loop. Beside angular position cues, haptic rotations furthermore provide continuous or stepwise force feedback, respectively accounting for a knob's constant resistance or presence of detents [2]. Studies have found that haptic rotations can be employed in safety-critical applications or when attention is required on concurrent tasks, such as during piloting or driving [3], [4].

In working environments such as food services and laundries, the lifetime of mechanical knobs is often limited by mechanical wear, seepage of liquids or dirt, accidental shock and vandalism. At the same time the use of virtual knobs on touchscreen has several disadvantages: firstly, the lack of grip makes non-visual control impossible; moreover, when interaction relies on peripheral vision due to concurrent tasks, rotation time and precision are negatively affected [5]; finally, despite being displayed as circular objects, virtual knobs require different interaction primitives as they are usually operated by touching them and then sliding with one finger on the screen across a straight line.

The main funder of this research conducted surveys with customers and professionals, pointing out that a robust solution alternative to touchscreen-based control would be desirable. However, the replacement of rotary mechanical knobs with robust mechanisms providing equivalent interaction primitives is not trivial. We propose a knob without moving parts, meanwhile capable of encoding rotation: a fixed cylinder whose side surface senses rotation gestures. Our design brings together advantages belonging to both physical and virtual knobs: a protruding cylinder can be grasped and operated without visual attention, and its lack of mechanical parts and gaps is immune to wear and to seepage of dirt and liquids. At the same time such design poses potential issues which are both perceptual and technical, such as its affordance of use, proprioceptive coherence and sensing accuracy. In an aim to gain insight about these issues, an experiment was set up to measure objective and subjective differences occurring when rotation gestures are respectively performed on a rotary or motionless knob.

Studies on tangible rotary input controllers [6], [5] revealed faster and more reliable interactions as compared to their virtual counterparts. Furthermore, they provide a measurable affective response [7]. Concerning the proprioceptive aspects of haptic rotation in general, rods have been used in orientation reproduction tasks to assess perceived parallelism and oblique effects [8], [9]. Additionally, haptic rotation was evaluated on an interface equivalent to a rotary knob: Krieger *et al.* tested whether the shape of a handle (e.g. rounded, edged, flat), the number of fingers, or the initial angular position influenced accuracy and precision. They found that round shapes provide the lowest precision [1], whereas increasing from 2 to 5 the number of fingers grasping the handle led to greater accuracy; on the other hand, the initial angular position affected rotation precision in terms of repeatability of the task, but not in terms of accuracy, with better results associated with the horizontal grasping position [10]. Also, rotation excess (overshooting) frequently took place. In parallel, rotation gestures have been studied on touchscreens, that is under visual-tactile conditions, especially considering gestures made with two fingers. A study involving 90° rotations [11] showed multiple outcomes: gesture duration and ergonomic failures increased with the distance existing between the fingers, furthermore depending on the initial angular position and rotation direction; concerning motor control, instead, Olafsdottir *et al.* found that awareness of the target angle helps optimize the initial position [12].

The studies mentioned above did not consider motionless knobs. In front of this knowledge gap, our work was inspired by the experimental design and performance metrics pro-

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posed by Krieger et al. [10]. A custom device was designed for the specific purpose of measuring task accuracy with a rotary vs. motionless knob. Being novel and untested, the device needed to be evaluated in its turn. We decided to conduct such evaluation as part of the main test, by switching our prototype to a motionless or rotating mode: if participants in fact produced the same haptic rotations using the standard rotary knob (i.e. routine condition) and using our device when set to be rotary, then a gesture on the same device in motionless mode would likely produce useful data for a comparative task analysis between a rotary and a motionless knob. With this premise in mind, the paper first details the characteristics of the device as an essential part of the setup. Then, the experimental design is described with attention to the task involving *routine* rotations (i.e. rotations of a standard rotary knob), finger sliding *gestures* around our motionless knob, and *rotations* of the same interface however set to be rotary. Finally, a discussion is provided focusing in particular on the affordability and potential of the motionless knob as a new technology, for which no prior literature offered a perspective yet.

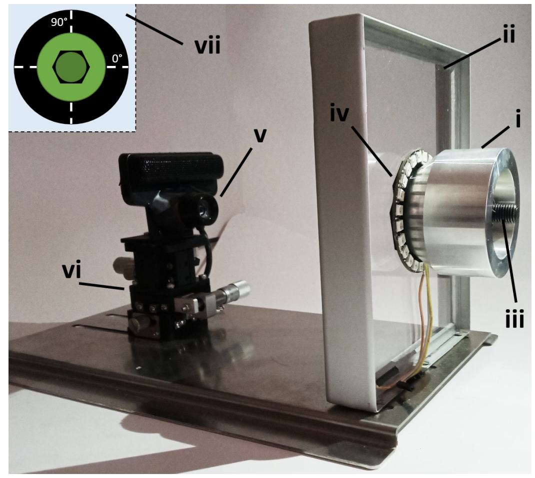


Fig. 1: Finger tracker: a metal cylinder (i) is fixed onto a Plexiglas panel (ii) by means of a M10 bolt (iii); a ring containing 24 LEDs (iv) illuminates the fingertips grasping the cylinder; on the back of the panel, a high-speed camera (v) standing on an adjustable metal support (vi) shoots the back side of the end-effector (vii).

II. Setup

Two knobs were made for the experiment, based on different principles yet offering an identical handle to the user: one was a standard rotary knob driving an electro-mechanical encoder; the other was instead built around an optical finger tracker as explained in what follows.

A. Optical finger tracker

The finger tracker, shown in Fig. 1, was based on a self-developed optical system and an aluminum cylinder around which fingers could comfortably slide. The cylinder had an external diameter equal to 65 mm, in compliance with ergonomics studies [13]. The inner side was further milled to host a WS2812 24-LED ring, used for illuminating the user's fingertips. The cylinder was fixed to a 200×300 mm Plexiglas panel by means of an M10 bolt. The role of the bolt was twofold, respectively to accommodate the switching of the interface in motionless or rotary mode: first it provided a reference point for the finger tracking algorithm; second, it acted as a pivot for the cylinder, also allowing to adjust its resistance against rotation. To this end, a half-threaded bolt having a straight neck of 20 mm was used: this way, the cylinder rotated with low resistance when the bolt was fully screwed-in, whereas it could be firmly locked by adding a 2 mm thick washer. The Plexiglas panel was mounted perpendicularly to a metal support which hosted a platform enabling micrometric adjustment of the position, pan and tilt of a Sony PlayStation Eye high-speed camera (60 fps @ 640×480 pixel resolution) facing the back of the panel.

1) Focal alignment and validation: A preliminary calibration procedure was needed to align the camera with the cylinder: to this end, a plastic ring (internal ⌀ = 65 mm, external ⌀ = 85 mm) was placed around the cylinder, then the support was adjusted so as to align and center the camera with three reference markers: a disc on the bolt head, a ring around it, and the mentioned outer plastic ring around the cylinder. To assess the accuracy of alignment and tracking, three white circular spots surrounded by a black background were glued at the side of the plastic ring, thus simulating three illuminated fingertips facing the camera, and 64 random rotations of the cylinder were recorded. The tracking algorithm (see below) was then applied to the recordings: the resulting error ranged between 0.15° and 1.46°, with mean standard deviation of 0.64°. The error was evenly distributed around the circumference of the cylinder, proving that the camera was correctly aligned.

2) Video processing: A software procedure was developed in Python 3.6 using OpenCV 4.1.2, which extracted dynamic positional data from illuminated fingertips and finally produced a video in which the fingertips are tagged with the same data, hence enabling human supervision of the tracking accuracy. The software first compensates for lens distortion [14] and then processes the data as follows (see Fig. 2):

1) the first video frame is presented to the operator, who draws with the mouse three bounding boxes around, in this order, the i) thumb, ii) index and iii) middle finger;
2) the bounded fingertips are then automatically tracked by the procedure using the CamShift algorithm [15]. Three small red circles are superimposed to the respective fingertips on each video frame, furthermore labeling them with the assigned ordinal number;
3) while displaying the last frame of the video, the procedure pauses and asks the operator to optionally adjust the position of the circles, in the case a mismatch occurred during tracking.

For each video recording, the software generates a list of frames containing the three fingers' (x, y) coordinate

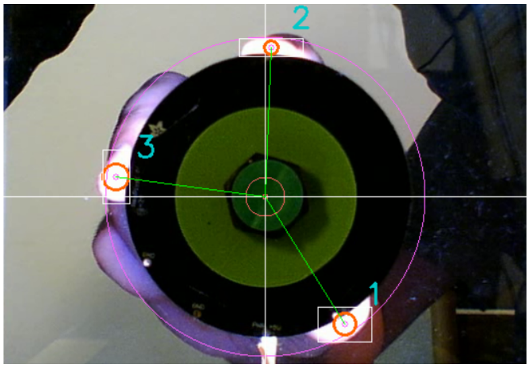


Fig. 2: Tracking of three illuminated fingertips (small red circles) within the bounding circular region (large violet circle). A white cross marks the center reference.

pair and the respective angle. The difference between the last and the first frame in each list is used to compute rotations, resulting in the following information for each video recording: initial angle, final angle and total rotation of each finger, average rotation of all fingers and related standard deviation.

B. Standard rotary knob

A metal knob identical to that of the finger tracker was fixed to a vertical metal panel having the same size and attach points of the finger tracker. The knob was connected to an AMS 5600 magnetic encoder having a resolution of 0.1°, which was connected to the PC used for the experiment and asynchronously read through the serial channel.

C. Trial control

Finally, a device was built to let participants record or repeat trials via two buttons labeled respectively REC and UNDO, both hosted by an Arduino UNO board. When the standard knob was in use, the REC button enabled the recording of the data from the encoder; conversely, when the finger tracker was used, the same button switched on the LED ring along with starting video recording. The UNDO button was used by participants who would like to repeat the latest trial.

III. Experiment

A. Participants

Sixteen people (9 males, 7 females) aged between 22 and 45 years (M=28.6, SD=5.95) took part in the experiment. None of them reported visual or sensorimotor impairments. All subjects but one were right-handed. They all participated on a voluntary basis and were not paid.

B. Procedure and task

Before each session, participants were briefed on the experimental procedure: the instructions for using the setup were displayed on a computer screen and further clarified by the experimenter. In particular, the experimenter checked that each participant had a clear mental representation of the target angles used in the experiment (45° and 90°, see Fig. 3). Consistently with the computer vision part of the setup, participants were instructed to always operate the knobs by using the thumb, index and middle finger. This reduced the factors in the experiment, meanwhile preserving comfortable rotation gestures.

Fig. 3: Participant grasping the knob while reading the rotation to be performed (i.e. 45° counterclockwise).

The standard and optically tracked knobs were placed side by side, both covered with a dark cloth as in Fig. 3, thus preventing participants to see the devices and their hands while performing the experiment. Participants sat in front of the computer screen and adjusted their arm position to comfort while grasping the metal cylinders with their dominant hand. Then, they were instructed to operate the trial-control device with the non-dominant hand, and to attend the computer screen across the entire experiment.

In each trial, as soon as a target rotation angle was displayed on the screen, participants had to i) grasp the current knob, ii) press and hold the REC button, iii) perform the requested rotation and, finally, iv) release the REC button. During the recording phase, a red dot was displayed on the screen; after the recording was stopped, participants were allowed to press the UNDO button if they were not satisfied with their performance and wished to repeat the trial.

At the end of the session, a questionnaire was proposed asking participants to rate the naturalness and pleasantness of the interaction with the input devices, as well as their immediacy of use.

C. Experimental design

The experiment followed a within-subjects design, in which participants compared three knob configurations:

- Routine: participants rotated the standard knob. This configuration served as a control for the experiment.
- Rotation: participants rotated the handle of the optical finger tracker set free to rotate.
- Gesture: participants performed a rotation gesture by sliding their fingers around the finger tracker set to be motionless.

All subjects performed a 3 blocks of trials, one for each of the three knob configurations.

Two factors were crossed: Configuration (Routine, Rotation, Gesture) and Angle (-90°, -45°, 45°, 90°), for a total of 3×4=12 factor combinations. Each combination was repeated 8 times, resulting in 96 trials per participant.

Half participants performed Routine as the first block, and the other half performed it as the last block; Gesture and Rotation were then randomly balanced across the two blocks left. The 32 trials within each block were also randomized.

No time limit was forced for completing the task. Each session lasted between 30 to 40 minutes.

D. Dependent variables

After being collected in lists of frames and optional manual correction (see Sec. II-A.2), data were merged in a single comma separated value (CSV) file. On such data, signed errors were differently calculated for each trial depending on the respective configuration: for the Routine configuration, as the angular difference between the target and recorded knob rotation; for the Gesture and Rotation configurations, as the angular difference between the target and average rotation operated by the fingers. Then, following the literature [10], [9], four dependent variables were calculated separately for each factor combination: mean signed error, variable error, finger deviation and initial position.

- The mean signed error was computed by averaging the signed errors across repetitions. Positive values (i.e. rotations on average larger than the target angle) correspond to overshoots, whereas negative values correspond to undershoots. Furthermore, smaller absolute values of this error signify higher *accuracy*.
- The variable error was computed as the standard deviation of the signed errors across the eight repetitions. Smaller values signify higher *precision*.
- The finger deviation was computed, limited to Rotation and Gesture, as the mean standard deviation of the signed errors belonging to each individual finger.
- The initial position was measured for the thumb and gave a picture of the participants' initial hand posture, again limited to Rotation and Gesture configurations.

IV. Results

A statistical analysis was conducted to check whether the four dependent variables were significantly affected by the two factors. Additionally, Sec. IV-D reports a descriptive statistics of the participants' answers to the questionnaire.

Separate analyses were carried out for the dependent variables, as they were found to be uncorrelated (Pearson Index≈0, p-values≫0.05) except for the pair mean signed error–variable error, resulting in a moderate positive correlation (Pearson Index=0.48, p<0.01). In order to keep type I error under control, standard confidence thresholds $\alpha = 0.05$ were Bonferroni-corrected over the dependent variables: $\alpha/4 = 0.0125$ [16].

A. Mean signed and variable error

Table I shows mean signed error and variable error distributions across configurations. The correlation existing between mean signed and variable errors suggests that accuracy paired with precision of the task. Moreover, means (M), medians (Mdn) and standard deviations (SD) are similar across configurations. In this regard, an analysis of the distributions was carried out on individual factor combinations, revealing severe violations of the ANOVA assumptions for both dependent variables due to the presence of outliers and deviations from normality [17]. Separate two-sided Friedman's tests [18] hence were performed for the mean signed and variable errors, considering each factor combination as a condition: no significant differences were detected (Q=7.21, p=0.78 for mean signed error; Q=12.1, p=0.36 for variable error), meaning that no combination of the two factors affected significantly either variable. For the Rotation and Gesture configurations, the mean signed and variable errors were further computed separately for each finger, however no effects associated to a specific finger were found.

TABLE I: Mean signed and variable error distributions across configurations: columns reports means (M), medians (Mdn), standard deviations (SD) and standard errors (SE).

	Routine		Rotation		Gesture	
	signed	variab.	signed	variab.	signed	variab.
M	14.7°	11.5°	13.3°	10.9°	14.4°	11.0°
Mdn	15.3°	11.2°	11.1°	9.3°	7.5°	9.5°
SD	±19.5°	±5.8°	±21.4°	±6.9°	±21.8°	±6.0°
SE	2.45°	0.72°	2.69°	0.87°	2.74°	0.76°

B. Finger deviation

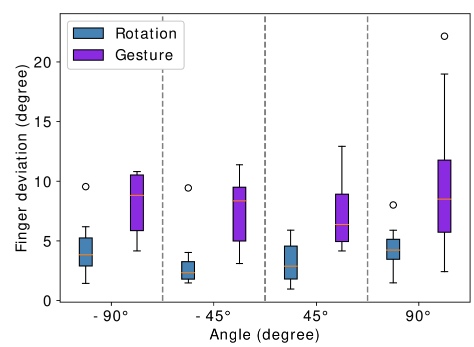


Fig. 4: Boxplot of finger deviation in Rotation and Gesture configurations for each angle.

Figure 4 shows boxplots of finger deviation in Rotation and Gesture configurations for each angle. As expected, the finger deviation for Rotation was close to zero, resulting in a flooring effect affecting the distributions. Therefore, a non-parametric analysis was performed considering in turn each factor combination as one of eight conditions of a combination factor (i.e. 2 configurations × 4 angles). Friedman's tests revealed significant differences (Q=63.85, p<0.01), suggesting to perform multiple pairwise comparisons using the Wilcoxon Rank-sum test [19] with Bonferroni correction. Such comparisons were carried out by grouping all conditions sharing the same configuration: They revealed that finger deviation in Rotation was significantly smaller than in Gesture (Z=-7.61, $p<0.01$). On the other hand, pairwise comparison of conditions sharing the same angle amplitude (i.e. $45°$ or $90°$) did not reveal significant differences (Z=-2.15, p=0.09). Pairwise comparison of conditions grouped by direction (i.e. clockwise and counterclockwise) did not reveal significant differences too (Z=0.19, p=0.84).

C. Initial position

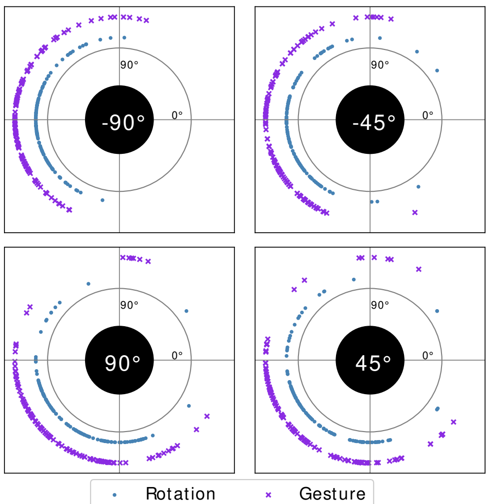


Fig. 5: Initial position of the thumb across the four angles in Rotation and Gesture configurations.

Figure 5 shows the initial positions of the thumb in each trial, grouped by Angle and Configuration, showing that they were more similar when the angle was equal to -90°. As data were distributed far from the zero degree reference, circular statistic was not needed. Again, due to violations of the ANOVA assumptions, a non-parametric analysis was performed revealing significant differences (Q=259.8, $p<0.01$). Pairwise comparison of direction (clockwise, counterclockwise) resulted in significant differences (Z=-15.31, $p<0.01$). On the other hand, pairwise comparisons carried out by grouping conditions with the same aperture of the angle ($45°$ or $90°$) revealed no significant differences (Z=-0.75, p=0.45), and so were pairwise comparisons grouping all conditions sharing the same configuration (Z=-0.34, p=0.73).

D. Questionnaires

Figure 6 reports the participants' answers to the questionnaire. Figure 6a compares the 5-points Likert scale distributions of the perceived naturalness while performing the task in the Gesture, Rotation and Control configurations. The distributions of Rotation and Routine are quite similar, whereas Gesture scored worse. The same trend is visible in Fig. 6b and Fig. 6c, respectively showing the pleasantness and easiness to reach the target.

V. Discussion

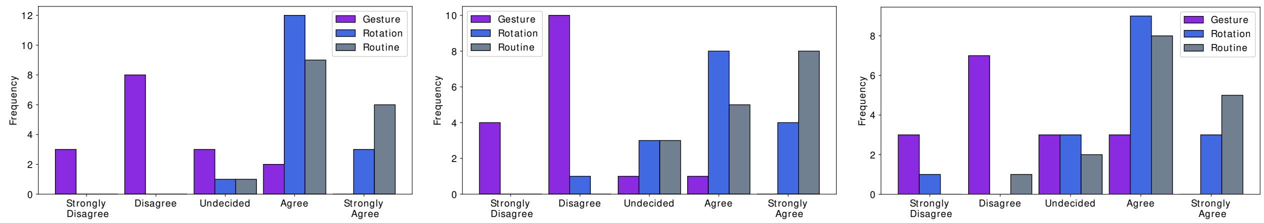
Previous literature on haptic rotation [1], [10], reports overshooting by about 10-15° during a rotation task. In our experiment overshoots took place independently of the configuration and angle, confirming such findings. Mean signed and variable errors were not affected by the independent variables, suggesting stability of the task in terms of accuracy and precision. Although the lack of significant differences in the dependent variables might be also ascribed to the relatively low number of participants (N=16), the individual distributions of factor combinations did not show any particular trend or deviation (see Table I), suggesting that should significant differences emerge by involving a larger pool of participants, they would have limited effects on the control of the input device compared to accuracy and precision of users. The especially high similarity of the results in Routine and Rotation confirmed the accuracy of our optical device compared to a standard encoder. The rest of the discussion, hence, focuses on differences arising between Rotation and Gesture.

Regarding the effects played by the independent variables, the configuration had an effect on finger deviation. This is not surprising, since the participants' fingers adhered to the knob while performing a Rotation task, whereas they had to slide over it during a Gesture task: in this configuration each finger followed its own trajectory. However, the similarity between the mean signed and variable error in such two different contact interactions suggests that participants in both cases relied on a robust proprioception, probably referred to different parts of their forearm during the task.

Remarkably, angle had no effect on the dependent variables, resulting in several implications. First, it implies that accuracy and precision are not relative to rotation angle, suggesting that both depend on a local process which is activated in the proximity of the target. Secondly, finger deviation is not proportional to rotations e.g. requiring the completion of a larger angle. Finally, not even the initial hand posture is in relation with the aperture of the angle that must be produced (see Fig. 5), although it depends on direction: this dependence may be possibly due to the existence of an end-state comfort effect [20].

In spite of their objective similarity, Rotation and Gesture received different preference levels. The generally negative ratings received by Gesture can be almost certainly ascribed to the fact that rotating a motionless knob is not natural. Indeed, rubbing upon an object that is otherwise expected to rotate below the fingers is in general unpleasant. Incidentally the tests took place during summer, when temperature and humidity may have amplified an uncomfortable feeling of finger contact interaction with the knob handle. Finally, negative ratings were similarly distributed across questions; this distribution suggests that the task would have been perceived as easier, holding a more pleasant and natural interaction.

As Table I shows, the participants' preferences are counterbalanced by the objective results: indeed, the mean signed error in the Gesture configuration actually scored the lowest median. However, as shown in Fig. 6c, this likely happened at the cost of a bigger effort in completing the task.



(a) Q: I feel the interaction is natural. (b) Q: I feel the interaction is pleasant. (c) Q: It is easy to reach the target position.

Fig. 6: Responses to the 5-point Likert scales on the perceived naturalness, pleasantness and easiness to reach the target.

VI. Conclusions

This study can be of help for the validation of technologies for the detection of rotation gestures beyond standard knobs. Some firm points concern the error rates: these proved to be independent of the angle within ranges of $90°$, despite a larger deviation among the fingers touching the motionless interface. As a consequence, future designs could avoid to memorize and process trajectories of the fingers during a rotation. Conversely, a gestural recognition system should focus just on the fingers' instantaneous positions, and treat their deviations independently of the rotation angle. The experiment also revealed that the variability of these positions around a motionless knob may be the main hindrance to a precise angle detection, especially if considering the different gestures that users can perform by involving a variable number of contacting fingers. In this regard, existing detection technologies include resistive and capacitive sensing: while the former would require the sensors to be on the external part of the motionless knob to obtain a precise detection [21], the latter could find place beneath a plastic casing providing measurements of self-capacitance. In spite of their generally low spatial discrimination – especially when fingers grasp the knob close to each other – capacitive sensors look promising for normal operating conditions, once provided with some intelligent post-processing of the sensed data.

Most importantly, participants rated the interaction with a motionless knob as less pleasant and natural. Assuming that some adaptation on new interactions is generally beneficial for their acceptance, this situation calls for an effort in the industrial design of surface materials making a motionless knob enjoyable by users.

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