KinesTouch: 3D Force-Feedback Rendering for Tactile Surfaces

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Abstract. In this paper, we introduce the KinesTouch, a novel approach for tactile screen enhancement providing four types of haptic feedback with a single force-feedback device: compliance, friction, fine roughness, and shape. We present the design and implementation of a corresponding set of haptic effects as well as a proof-of-concept setup. Regarding friction in particular, we propose a novel effect based on large lateral motion that increases or diminishes the sliding velocity between the finger and the screen. A user study was conducted on this effect to confirm its ability to produce distinct sliding sensations. Visual cues were confirmed to influence sliding judgments, but further studies would help clarifying the role of tactile cues. Finally, we showcase several use cases illustrating the possibilities offered by the KinesTouch to enhance 2D and 3D interactions on tactile screens in various contexts.

Keywords: Touchscreen · Surface haptics · Sliding · Force feedback

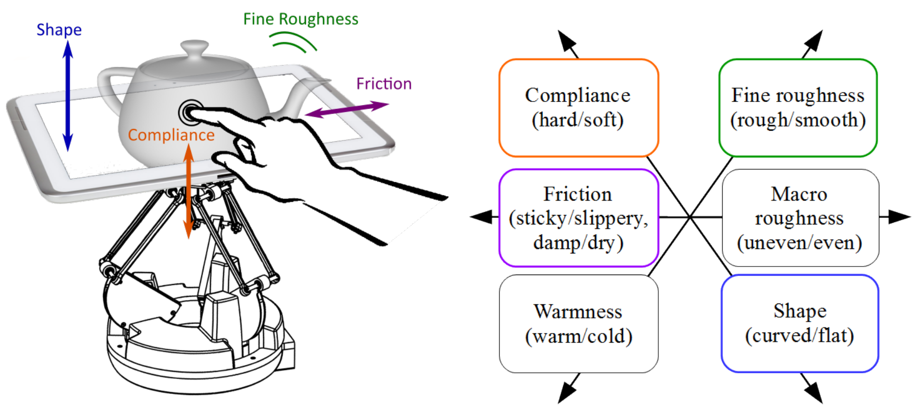
1 Introduction

Touchscreens have become ubiquitous in human-computer interaction. They enable freehand direct interaction with 2D and 3D content and they are effectively used in numerous applications. They can be found everywhere, from public ticket machines to mobile phones and laptops.

Despite their intrinsic qualities, as for today, touchscreens still often lack tactile sensations. Irrespective of the visual content, they feel flat, rigid, smooth and static under the finger. Although touchscreens take advantage of finger dexterity, they do not exploit finger sensitivity.

The haptic enhancement of touchscreens is a relatively young and active research field known as "surface haptics" [7]. An impressive amount of work has already been done to conceive and develop such technologies in the last decade [36] [3] [19] [23] [35]. Most efforts have been concentrated on generating various types of vibration that can alter the physics of the finger sliding on the screen, providing friction and even small relief sensations [36] [17]. However, such approaches do not allow to display other haptic properties such as stiffness or large-scale shapes.

A few solutions have proposed a touchscreen with kinesthetic feedback, i.e., able to move in space rather than vibrate, in order to involve spatial proprioception. Some approaches used parallel platforms for co-localized inclination rendering [16] [20], eventually combined with variable friction [10], but they kept a focus on rendering geometric features rather than material properties like stiffness, slipperiness or roughness. Sinclair et al. have proposed a remarkable solution combining 1-DoF kinesthetic and force feedback [28] [29], showcasing many interesting perceptual and interaction possibilities. Yet, besides its limitation to one axis, their device remains cumbersome and complex to spread out. The work of Takanaka et al. [30] is the only one, to our knowledge, to provide a touchscreen with lateral motion to evoke haptic properties. Interestingly, they chose to keep a non-slipping contact with the screen and simulated inertia and stiffness rather than sliding the screen against the finger to simulate friction or slipperiness. Although many innovative technologies have been developed to provide co-localized friction effects, the potential of the lateral motion of the screen under the finger has not been investigated yet.



(a) The KinesTouch concept.

(b) The six dimensions of surface haptics, adapted from Okamoto et al. [24].

Fig. 1: The KinesTouch approach provides four different types of haptic feedback to a touchscreen.

In this paper, we propose to use a single force-feedback device to provide four different types of haptic feedback to a tactile tablet: Shape, Stiffness, Roughness, and Sliding (see Figure 1). In particular, our Sliding effect alters the sliding velocity of the finger on the screen through large lateral movements, which constitute a novel approach in friction rendering.

In the remainder of this paper, we first present related work on surface haptics in the light of haptic perception of surfaces. Then, the KinesTouch concept is introduced together with our set of haptic effects. The technical feasibility of our approach is then demonstrated with a proof-of-concept prototype. The results of a user study focused on the Sliding effect are presented and discussed. Finally, several use cases of our system are exposed.

2 Related work

2.1 Dimensionality of surface haptics

The dimensionality of real and artificial textures perception has been investigated in manifold studies. In a survey paper synthesizing over forty years of research, Okamoto et al. proposed five psychophysical dimensions that synthesize state of the art results: 1) compliance (hardness), 2) friction, 3) fine roughness, 4) macro roughness, and 5) warmness [24] (see Figure 1b).

Yem and Kajimoto [39] suggested a correspondence between these five dimensions and the different types of tactile receptors in the skin. The four types of mechanoreceptors are known to be especially receptive to a specific stimuli: static pressure for SA-1, local deformation of the skin for SA-II, rapid lateral skin stretch for FA-I and high frequency vibrations for FA-II [14]. In addition, thermoreceptors are responsible for temperature gradient sensing [9]. Like Okamoto et al., they did not consider the kinesthetic sense, that is the perception of one's body movements, which is crucial to perceive large scale shapes.

The division between fine and macro roughness, was confirmed by several studies [11] [12] [4] many decades after it was hypothesized by Katz [15] under the famous name of "duplex theory". This theory states that fine and coarse asperities are mediated by two distinct perceptual mechanisms, the first one relying on contact vibrations and the second one involving pressure spatial distribution. It was notably found that contact vibrations are necessary to perceive asperities under 0.1mm, indicating a perceptual shift around this scale [12]. It is noticeable that these two properties are spontaneously explored with two distinct strategies, namely lateral motion and static contact. These two "exploratory movements", identified by Lederman and Klatsky decades ago [18], are appropriate ways to elicit the most relevant stimulus, namely static pressure distribution or rubbing vibrations.

Another exploratory movement named "contour following" [18], aims at inspecting the global shape or volume of an object with large movements. In this case the kinesthesia (or proprioception) is likely to be predominant in the perceptual process. Therefore, there should be a perceptual shift from macro roughness to shape similar to the one from fine to macro roughness. The location of this shift is obviously in the vicinity of a finger width, although it would be reasonable to expect some overlap, similarly to fine and macro roughness. In the remainder of this paper, we will call this sixth dimension the "shape" dimension.

2.2 Surface haptics systems

Vibrators and vibrotactile feedback have been early embedded in commercial touchscreen products and can be used for fine roughness simulation. But many researchers have proposed original ways to enrich touchscreens with an additional vibrator placed either on the nail [2], between several fingers and the screen [6], on the device [5] [38] [41] or both on the device and on haptic gloves [13]. In particular, Romano and Kuchenbecker used a high-quality one-dimensional vibration to display compelling texture details through an actuated stylus, according to normal contact force and lateral speed [25].

Several variable friction devices have been developed, either using ultrasonic vibration [19] [23] or electrovibration [3] [21]. In both approaches, friction can be modulated to produce texture effects and even 3D pattern features [36] [17]. Some researchers also chose to instrument the finger, either with vibrators [6] [2] or with a lateral-force proxy [37] [26] [27]. Several solutions producing mechanical planar vibrations [33] or short-range movements [22] were also proposed. However all these approaches had no force or motion abilities in the normal direction, and thus could not provide compliance and large shapes sensations.

Parallel platforms were used for co-localized curvature feedback [16], notably the "SurfTics" [10] and the "ForceTab" [20] devices. Another approach presented in [30] consists in a touchscreen with planar force feedback and large translation and rotation abilities. These approaches were focused on shape rendering and did not address other dimensions of haptic perception.

The "TouchMover" device [28] is a touchscreen actuated and moved using force feedback in the normal direction, showcasing interesting applications notably in volumetric data manipulation. The second version [29] includes vibrators that render fine shape details at contact point. The normal force-feedback allows for stiffness or inertia simulation and shape rendering, but no lateral friction sensations. Besides its limitation to one axis and two psychophysical dimensions, the TouchMover remains rather cumbersome and complex to spread out, involving custom and expensive mechanics and electronics.

There are actually rather few systems aiming at simulating a wider range of haptic sensations. The device designed by Yem and Kajimoto [39] is able to simulate up to four psychophysical dimensions of texture perception: compliance, friction, fine and macro roughness. But this system is finger-mounted and not touchscreen-based, and it does not co-localize visual and haptic displays. Culbertson and Kuchenbecker [8] combined a pen-shaped force-feedback rendering stickiness through tangential forces with an high-quality vibrator rendering hardness through tapping transients and fine roughness through vibrations.

Table 1 provides an overview of previous contributions in surface haptics, with the type of haptic sensation they have addressed. Interestingly enough, these previous systems are able to simulate only one or two psychophysical dimensions. Temperature and macro roughness were not taken into account here, as we could not find representative examples of touchscreen enhancement involving one of them combined with another dimension.

Table 1: Main previous approaches in surface haptics. Most of them address only one or two psychophysical dimensions.

Approach	References	Addressed psychophysical dimensions: Compliance	Friction	Shape	Fine Roughness
Normal force feedback	[28]	Stiffness	-	Shape	-
	[29]	Inertia	-	Shape	-
Normal kinesthetic feedback	[20]	-	-	Shape	-
Lateral force feedback	[22]	-	Static & reduced friction	Smooth bumps	-
	[26]	-	-	Bumps	-
	[27]	-	-	Bumps	Increased roughness
	[30]	Lateral stiffness	-	Lateral inertia	-
Lateral force feedback + vibrations	[8]	Tapping transients	Increased friction	-	Increased roughness
Rotational kinesthetic feedback	[40]	-	-	Curvature	-
	[16]	-	-	Curvature	-
	[10]	-	-	Curvature, Edges	-
Ultrasonic friction reduction	[34]	-	-	-	Reduced roughness
	[36]	-	Reduced friction	Edges, smooth bumps	-
	[23]	-	Reduced friction	-	-
Electrostatic friction amplification	[3]	-	Increased friction	-	-
	[17]	-	-	Bumps	-
Finger-mounted vibrations	[2]	-	-	Edges, bumps	-
	[6]	-	-	Edges, bumps	-
Electrotactile	[1]	-	-	-	Increased roughness
KinesTouch: 3D force and kinesthetic feedback		Stiffness	Increased sliding, reduced sliding	Shape, bumps, edges	Increased roughness

3 The KinesTouch approach

The KinesTouch approach enriches touchscreen interactions with a set of tactile and kinesthetic effects in both normal and lateral directions. When the user touches an object or an image displayed on the touchscreen, the screen is given forces or motion simulating various haptic properties: it can resist more or less to pressure to render material stiffness, move up and down according to object's shape, vibrate during a stroke to evoke texture roughness, or slide laterally to change the slipperiness sensations.

In the following sections, we present our set of four co-localized haptic effects. We will focus on the case of using a 3-DOF impedance device for the control law. But the KinesTouch approach is scalable and could be used with higher end 6-DoF haptic interfaces that could allow for even more effects than what we propose hereafter.

3.1 Notations

In the remainder of this paper, vectors and matrices will be expressed in the fixed reference frame with positive z upwards. The screen is considered to be horizontal, parallel to the xy plan. Also: $\boldsymbol{X}_0$ will refer to the 3D center position of the workspace, $\boldsymbol{X}_t$ will refer to the 3D screen position with respect to $\boldsymbol{X}_0$, $\boldsymbol{f}$ will refer to the 2D finger position on the screen, $\mathbf{I}_3$ will refer to the identity matrix, $\boldsymbol{e}_z$ will refer to the vertical unit vector, $K_{\max}$ will refer to a high stiffness value,depending on hardware performance, used for position control[3] (1 N/mm in our setup).

3.2 Stiffness effect

The Stiffness effect allows the user to feel a resistance to deformation when they push an object on the screen. It simulates the elasticity of a material, and address the compliance perceptual dimension. The effect consists in a normal opposing force that increases with penalty, as shown in Figure 2. The two other directions of the touchscreen are locked in position.

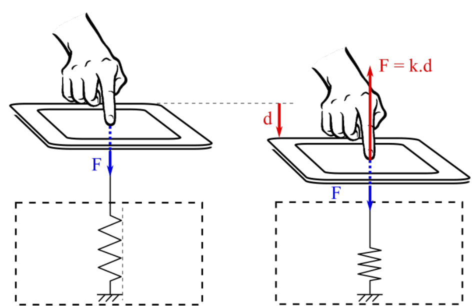


Fig. 2: Stiffness effect: the screen provides an elastic force under pressure.

Using an elastic deformation model, the control law of our Stiffness effect is:

$$\boldsymbol{F}_{\text{stiffness}} = \begin{bmatrix} K_{\max} & 0 & 0 \\ 0 & K_{\max} & 0 \\ 0 & 0 & k_{\text{mat}} \end{bmatrix} (\boldsymbol{X}_0 - \boldsymbol{X}_t) \tag{1}$$

with k_{mat} the simulated stiffness.

[3] Impedance force-feedback devices provide forces to their end-effector, while measuring its position. Although they can't act directly on position, they can still be used for pseudo position control with a high stiffness force linking the measured position to the desired one.

3.3 Shape effect

The Shape effect allows the user to feel the 3D shape of an object. It reproduces reliefs that are larger than a finger and need active exploration to be perceived. The effect consists in a normal displacement corresponding to the change in vertical projection of the 2D finger position on the object's 3D shape, as shown in Figure 3. The two other directions of the touchscreen are locked in position (i.e., there is no lateral motion).

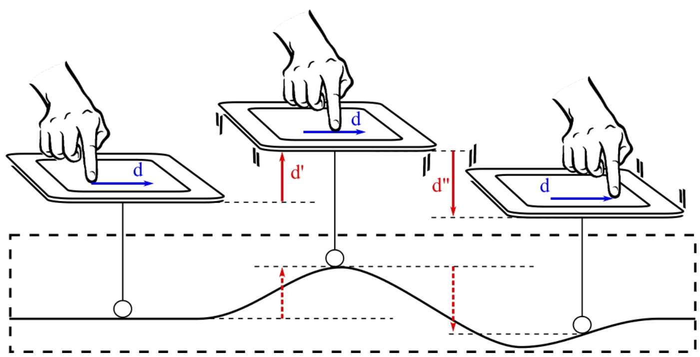


Fig. 3: Shape effect: the vertical displacement during stroke reproduces reliefs.

The control law of our Shape effect is:

$$\boldsymbol{F}_{\text{shape}} = K_{\max}\, \mathbf{I}_3\ (\boldsymbol{X}_0 + h(\boldsymbol{f})\ \boldsymbol{e}_z - \boldsymbol{X}_t) \tag{2}$$

with $h(x, y)$ the vertical projection of the finger position onto the 3D shape.

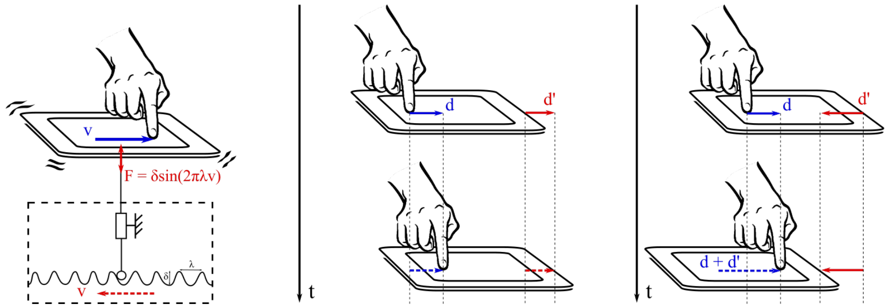
The shape is accessed "from the top": only its visible upper part, relatively to the horizontal plane, can be explored. However, a simple rotation of the shape in the virtual space allows to access its bottom part.

3.4 Roughness effect

The Roughness effect allows the user to feel vibrations evoking a periodic grating when they stroke an object on the screen. It renders the fine roughness property, modeled by a small spatial period. The effect consists in an oscillating force taking into account both the simulated spatial period and the finger exploration velocity, as shown in Figure 4a. The touchscreen is otherwise locked in position.

$$\boldsymbol{F}_{\text{roughness}} = \delta \sin(2\pi\lambda||\dot{\boldsymbol{f}}||)\ \boldsymbol{e}_z + K_{\max}\, \mathbf{I}_3\ (\boldsymbol{X}_0 - \boldsymbol{X}_t) \tag{3}$$

with δ the grating depth, λ the grating spatial period.



(a) Roughness effect. (b) Follow effect. (c) Reverse effect.

Fig. 4: Roughness effect: the screen vibrates during stroke to simulate roughness **(a)**. Sliding effect: the screen moves laterally to cancel **(b)** or increase **(c)** relative sliding.

3.5 Sliding effect

The Sliding effect provides various sliding sensations to the user when they stroke an object on the screen. As it modifies the sliding phenomenon between the screen and the finger, it addresses the friction perceptual dimension. It consists in a tangential movement of the screen meant to increase or diminish the relative sliding, that is the velocity difference, with the finger. We expect two different sensations corresponding to the two possible sliding directions: a "Follow effect" and a "Reverse effect" which are described hereafter. The touchscreen motion is locked here in position in the normal direction.

The "Follow effect", illustrated in Figure 4b, consists in moving the screen the same way the finger moves on the screen, so that relative sliding is decreased or even kept close to zero. In this case, while the finger moves in the reference frame, its position on the screen remains almost static.

The "Reverse effect", illustrated in Figure 4c, consists in moving the screen in the opposite direction to finger's movement, so that relative sliding is increased.

The Sliding effect is achieved with the combination of two forces: a "moving force" proportional to finger's tangential velocity, and a damping force in the binormal direction:

$$\boldsymbol{F}_{\text{slipperiness}} = \alpha \ \dot{\boldsymbol{f}} - \nu \ \dot{\boldsymbol{f}} \wedge \boldsymbol{e}_z + K_{\max} \ (\boldsymbol{X}_0 \cdot \boldsymbol{e}_z - \boldsymbol{X}_t \cdot \boldsymbol{e}_z) \tag{4}$$

with $\alpha \in [-1, 1]$ the slipperiness coefficient and ν the damping coefficient.

3.6 Idle behavior

When the screen is not touched, it should stay still or move back to the center of the workspace, so that the force-feedback device remains close to its neutral position. This is done by applying a simple centering force instead of one of the previous effects:

$$\boldsymbol{F}_{idle} = K_{\max}\ \mathbf{I}_3\ (\boldsymbol{X}_0 - \boldsymbol{X}_t) \tag{5}$$

4 The KinesTouch prototype

In this section, we describe the design and implementation of our prototype using a standard tablet and Novint Falcon haptic device. We designed a custom end-effector in order to be able to attach the tablet on the haptic device handle, and a prediction-correction algorithm to compensate the touch tracking latency. We also present the handling of synchronization between visual and haptic loops, and the control law for the haptic rendering.

4.1 Hardware

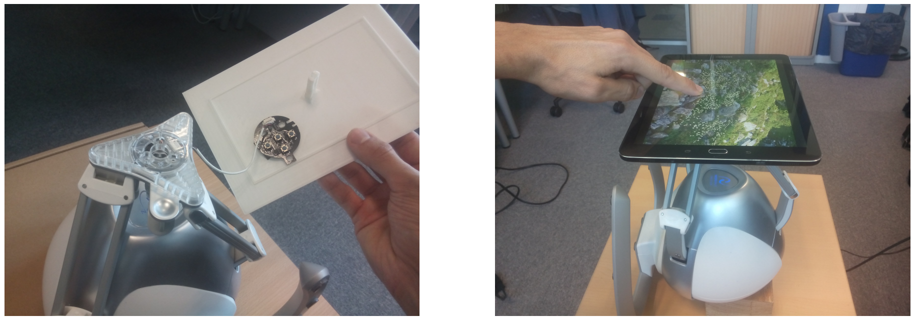
The Falcon is a standard 3-DoF impedance haptic device, initially designed for the gaming industry. We combined it with a Galaxy Tab SM-T810, which exhibits rather high resolution (2048x1536), comfortable size (9.7”) and an acceptable weight (389g).

Assembly of tablet and force-feedback device The Falcon’s grip has several buttons and is removable, but a security mechanism deactivates the device when the grip is removed, detecting the electrical contact with the grip. This problem was overcome by unmounting the default grip and keeping only the coupling part and electronic circuit. A tablet adapter, shown in Figure 5a, that reproduced the interlock while offering a flat shape to affix the tablet, was 3D-printed. As the precise relative positioning of the tablet was not of importance for the haptic effects presented in this paper, it was affixed to the adapter with a simple velcro grip. The Falcon was then rotated by 90 degrees and positioned sideways so that it “pushed forward” the tablet vertically, as shown in Figure 5b.

4.2 Software

Handling latency issues Besides the visual display, the tablet application is also responsible for touch tracking and filtering. In practice, the built-in touch tracking of the Galaxy Tab SM-T810 has a latency of a few dozens of ms, and the Unity application has a refresh rate of 60 Hz. This results in a delay in the position measurement up to 2 cm in usual slide movements, which is problematic for real-time haptic rendering. Furthermore, despite the high resolution of the screen, instantaneous touch velocity estimation suffers from spikes due to pixel quantization. For these reasons, touch position and velocity were computed and filtered before being sent and used in the haptic rendering loop, according to the following prediction algorithm, inspired from [31].

First, measured touch position $\boldsymbol{f}_{\text{mes}}$ is converted in real-world meter coordinates. Then, a simple linear prediction is applied to measured touched position:



(a) 3D printed adapter. (b) Global setup.

Fig. 5: KinesTouch prototype.

$$\boldsymbol{f}_{\text{pred}} = \boldsymbol{f}_{\text{mes}} + k_{\text{pred}} * (\boldsymbol{f}_{\text{mes}} - \boldsymbol{f}_{\text{mes}}^{prev}) \tag{6}$$

where f_{mes}^{prev} is the previous measured touch position and k_{pred} the filter parameter.

Finally, an exponential smoothing filter is applied to get the corrected position:

$$\boldsymbol{f} = \alpha * \boldsymbol{f}_{\text{pred}}(1 - \alpha) * \boldsymbol{f}_{\text{pred}}^{prev} \tag{7}$$

where $\boldsymbol{f}_{\text{pred}}^{prev}$ is the previous predicted position and α the filter parameter.

The parameters were set after testings to: $k_{\text{pred}} = 8$ and $\alpha = 0.15$.

Instantaneous touch velocity is smoothed with an exponential smoothing filter with $\alpha = 0.45$.

Visual and haptic loops synchronization The haptic rendering is computed by a dedicated application running on a laptop and using the CHAI3D framework[4]. On the tablet, a Unity application is used for the visual rendering and the touch tracking. The two applications communicate with each other using the Open Sound Control (OSC) protocol[5]. As applications run at different rates, this communication is asynchronous. On both sides, incoming messages are treated in a specific thread and update global variable values which are then used in the main thread. A network connection is emulated through the USB cable connecting the tablet and the laptop, so that OSC communication latency is kept under 1ms.

The haptic rendering is mostly located in a haptic thread running at about 1000 Hz inside the CHAI3D application. An additional 60 Hz thread is meant to send the Falcon position to the tablet application. The synchronization of

[4] http://chai3d.org/download/license
[5] http://opensoundcontrol.org/introduction-osc

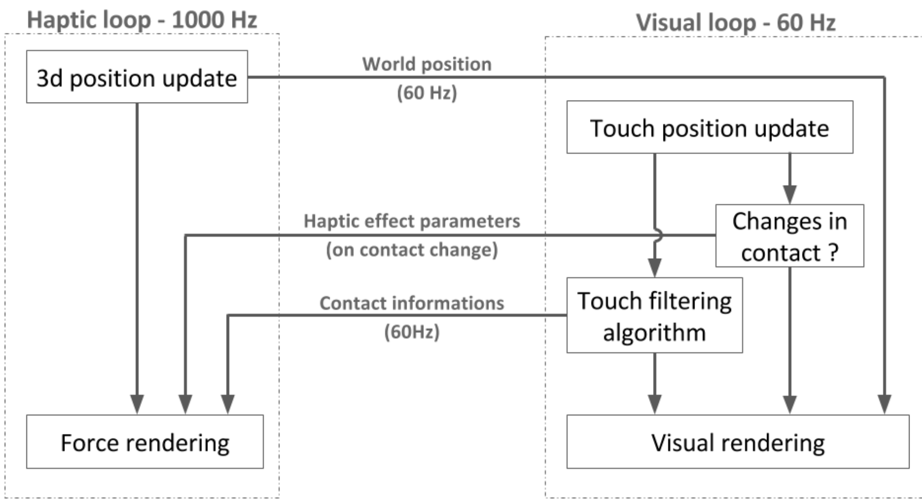


Fig. 6: Software architecture

the two loops is illustrated in Figure 6. In the Unity application, a main loop updates touch information, sends them to the CHAI3D application, and updates the visual display. This visual display compensates the Falcon movements so that when the tablet is moving, displayed objects remain immobile in the user's reference frame.

Transparency In the previous descriptions of our haptic effects, the system is supposed to be perfectly transparent, with no inertia. However the weight of the touchscreen and effector are not negligible compared to the other involved forces, and have to be compensated by adding a constant opposite force in the control law.

4.3 Control law

The final haptic rendering was obtained using a single control law that merged all our haptic effects:

$$\begin{aligned}\boldsymbol{F}_{\text{total}} = (mg + \delta\sin(2\pi\lambda||\dot{\boldsymbol{f}}||))\boldsymbol{e}_z + \alpha\dot{\boldsymbol{f}} - \nu\dot{\boldsymbol{f}} \wedge \boldsymbol{e}_z \\ +\mathbf{K}\ (\boldsymbol{X}_0 + h\boldsymbol{e}_z - \boldsymbol{X}_t)\end{aligned} \tag{8}$$

with $\mathbf{K}$ the stabilization matrix, given in Table 2.

The Falcon was found to produce forces proportional, but not equal, to the forces requested through the CHAI3D API. This problem was overcome by applying a gain factor that was empirically found to of about 4.5 on two different Falcon devices to get the right forces. This is consistent with another study, although they found the gain to be equal to 3 [32]. This difference of value might be explained by the difference of CHAI3D version.

Table 2: Stabilization matrix values for the different effects.

Effect	Idle, Shape, Roughness	Stiffness	Sliding
K	$K_{\max}\ \mathbf{I}_3$	$\begin{bmatrix} K_{\max} & 0 & 0 \\ 0 & K_{\max} & 0 \\ 0 & 0 & k_{\text{mat}} \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & K_{\max} \end{bmatrix}$

5 User study

5.1 Introduction

We conducted a user study to evaluate the sensations produced by the KinesTouch prototype. Due to the large variety of our haptic effects, we have focused on our most innovative effect: the Sliding effect. Our choice was motivated by the fact that equivalents of Stiffness, Shape and Roughness effects have already been largely studied in the haptic literature. In contrast, the Sliding effect had never been explored in the literature and there are no clear assumptions on what the user's perception will be. Thus, we conducted a user study to answer the following question: are users able to consistently and efficiently discriminate different Sliding effects?

We compared three sliding sensations: the Reverse effect (REVERSE, see Figure 4), the Follow effect (FOLLOW, see Figure 4), and a control stimulus in which the tablet stays static (STATIC). Three hypotheses were tested:

- **H1**: different stimuli would produce different sensations
- **H2**: seeing the moving screen contributes to distinguish between stimuli, i.e., visual cues increase the discrimination accuracy.
- **H3**: the smoothness of the screen diminishes the sensations produced, i.e., a tactile cues increase the discrimination accuracy.

5.2 Materials and methods

Procedure 18 volunteer unpaid subjects (16 male, age 31.2 ± 12.1) took part in the experiment which consisted in two sessions of about 45mn on different days. All of them were right-handed or ambidextrous.

After reading and signing a consent form, subjects were asked to seat with the right arm resting besides the tablet screen. For each trial, a narrow white area was displayed on the screen, and the subject was invited to slide their finger inside this area.

Each trial was composed of the active exploration of two stimuli, followed by a forced-choice question to designate on which one the subject felt the more sliding.Each stimuli lasted 3.5 seconds from the moment the screen was touched, then the screen turned to black and waited for the touch release to pass to the second stimulus or the question. The subject provided the answer to the question directly on the screen.

At the beginning of each session, two practice trials were first performed to ensure that subject understood the procedure. During these introductory trials, a moving target was displayed to suggest a back and forth movement at 0.5 Hz. Subjects were informed that the stimuli would be optimally felt within this range of velocities but were left free in their inspection otherwise.

Experimental Design The experiment had three independent variables: the stimulus, the visual cues (i.e., seeing the tablet moving) and the tactile cues (i.e., screen roughness). Three pairwise comparisons were considered: REVERSE vs. FOLLOW, REVERSE vs. STATIC and FOLLOW vs. STATIC. To avoid order effects, the inverse comparisons were also considered.

In order to evaluate the importance of visual cues, half of the trials were performed with the whole mechanism being visible (V1, see Figure 7a), and half with a black cover hiding the mechanism and its movements (V0, see Figure 7b). In order to evaluate the importance of tactile cues, half of the trials were performed with a window privacy film applied on the screen (F1) and half without (F0). This transparent and electro-statically adhesive film had small but clearly perceptible reliefs that produced quite strong vibrations under the finger when being stroked. Affixed to the screen, there was no decrease in brightness but a tiny pixel diffraction on each relief. Trials were split in four condition blocks corresponding to the visual and tactile crossed conditions: V0F0, V0F1, V1F0, V1F1. In order to avoid order effects, the order of the blocks was given by the Latin-square method. In each of the two sessions, two condition blocks of 60 trials (10 repetitions for each of the 6 pairwise combinations) were performed.

(a) The V1F0 condition (without cover). (b) The V0F0 condition (with cover).

Fig. 7: General setup without and with cover.

Collected data and scoring For each trial, the answer as well as the response time were recorded. In addition, a discrimination score for each subject was computed for each combination and factor (3 comparisons x 2 visual conditions x 2 tactile conditions). The discrimination score was computed as follows. First, each trial was counted as +1 or -1 according to stimulus chosen as the "more sliding" (the pair order being taken into account). For example, in a REVERSE vs. STATIC comparison, +1 will mean that REVERSE is considered to be more sliding that STATIC and vice-versa. Second, the data for each combination was normalized between [-1,1], showing the preference between the two stimuli. Finally, as we observed that subjects had different interpretations of the question, but were consistent in the stimulus they chose as "more sliding", we considered the absolute value of the discrimination score [0,1].

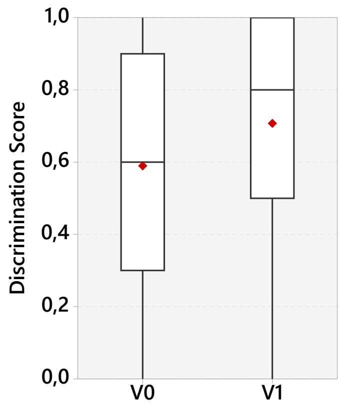
Thus, as indicated in Table 3, a discrimination score of 0 indicated that the subject had no preference between the two stimuli and answered randomly (with a 50% accuracy), whereas a discrimination score of 1 indicated that the subject consistently chose one stimulus over the other (with a 100% accuracy).

Table 3: Correspondence between preference rate and discrimination score.

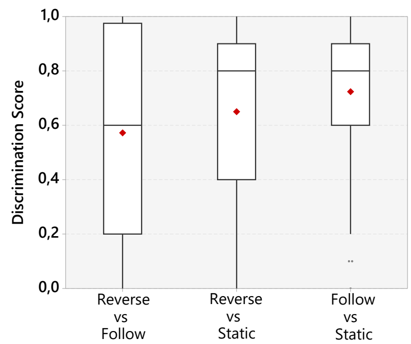
Preference rate	50%	60%	75%	80%	90%	95%	100%
Discrimination score	0	0.2	0.5	0.6	0.8	0.9	1

5.3 Results

Figure 8 show the distributions of the discrimination scores grouped according to the independent variables. On each figure, the red dot indicates the mean value, in addition to the median value and quartiles indicated by the box. An Anderson Darling normality test revealed that the data distribution were not normal, so we performed an aligned rank transform in order to enable a full factorial analysis using ANOVA. The three-way ANOVA comparison, visual and tactile cues vs. the discrimination score revealed a significant main effect on the visual condition ($F_{1,17}$ = 9.56, p < 0.01). Post-hoc tests showed that this effect was significant (p<0.05), V1 had a higher discrimination score ($M = 0.71$; $SD = 0.3$) compared with V0 ($M = 0.59$; $SD = 0.33$). These results support **H2**. In contrast, no main effect was found on the tactile condition ($F_{1,17} = 3.64$, p = 0.073). Yet, the results seems to suggest that there is an impact of the screen roughness: F0 ($M = 0.61$; $SD = 0.34$) compared to F1 ($M = 0.69$; $SD = 0.30$). Nevertheless the results do not support **H3**. Regarding the different comparisons, the ANOVA did not show a significant effect ($F_{2,17}$ = 3.00, p = 0.063). Again, the results are close to the significance threshold. Post-hoc tests seems to suggest that subjects were less accurate for the REVERSE vs. STATIC comparison (p=0.053). Finally, the ANOVA did not show any interaction effect.



(a) Visual condition (H2).



(b) Stimuli pairs.

Fig. 8: Score distributions across visuo-tactile conditions and stimuli pairs.

Figure 8a shows the score distributions according the visual condition. Scores were significantly higher in the V1 condition, that is with the mechanism visible, than in the V0 condition, that is with a cover hiding it. Scores were also higher, but not significantly, in the F1 condition than in the F0 condition, i.e., with the textured film on the tablet rather than without. The distributions of the crossed visuo-tactile conditions are consistent with the results of the non-crossed conditions (Figure 8a): scores were significantly higher with the mechanism visible, and not significantly higher with the textured film on the tablet rather than without. The highest average score is achieved, as expected, in the V1F1 condition, with half of the subjects having a score above 0.9.

Figure 8b shows that the scores were different regarding which stimuli were compared. When the Reverse and the Follow effects were compared, the scores are distributed quite uniformly between 0 and 1. In contrast, for the comparison between the Follow effect and the control condition, half of the subjects have a discrimination score above 0.8 and a few have a score close to zero.

5.4 Discussion

Our results suggest that our Sliding effect is well and consistently discriminated by a great majority of subjects. Indeed, even in the least favorable condition, V0F0, half of the subjects had a score above 0.6, which means they were consistent in at least 80% of their answers. In the most favorable condition, V1F1, half of the subjects had a score of 0.9 or higher, indicating 95% of their answers were consistent. It is noticeable that in most conditions, score distributions were very large, ranging from 0 to 1, meaning that some subjects answered randomly and some subjects answered with a perfect consistency. The mean values, however, are above 0.5 in all conditions, which means that in average, whatever the condition, the subjects were consistent in their classification on at least 75% of the trials. Moreover, in almost all conditions this mean value is slightly lower than the median value, which indicates that it is worn down by a few values close to 0.

These results demonstrate that the subjects' ability to discriminate between the three stimuli were generally well above the random threshold with or without visual and/or tactile cues. As expected, visual cues had significant positive impact on discrimination. More surprisingly, the rough textured film on the screen had only a minor effect. We were expecting it to make the difference between stimuli very clear, as it produces strong vibrations according to sliding speed, in contrast with the very smooth screen that does not provide much sliding sensations.

However, an unexpected side effect was that the textured film was much less sticky than the screen, so that although the tactile sensations were stronger, it was much easier to stroke it fast. We think that this could have biased the answer about the "sliding" sensation, and could explain why subjects had different strategies to rank the stimuli. During the experiment, we noticed that most users had a clear ranking for a given visuo-tactile condition, but it was not necessary the same when the visual or tactile condition changed.

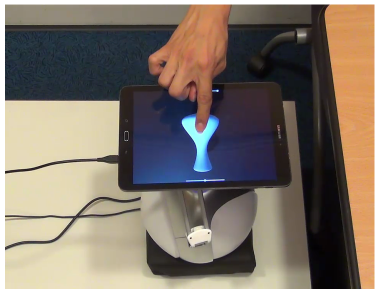
While the subjects were clearly able to discriminate the three stimuli, their ranking in terms of sliding was different among subjects and conditions. This might simply reflect the polysemy of the "sliding" term, and the very blurred vocabulary we have when it comes to describe tactile experiences. Further studies could disambiguate the sensations produced by the lateral sliding of the screen during stroke. For instance, asking the subjects about both roughness and sliding sensation could help to identify the dependence or independence of these two parameters. Also, a comparison with real material samples rather than between haptic effects might help avoiding misinterpretations and keep a low inter-subject variability.

6 Use cases

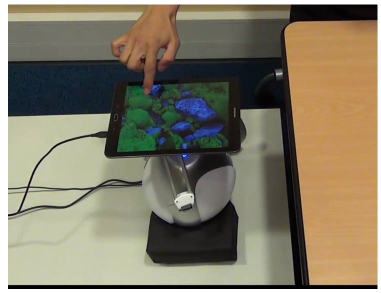
The KinesTouch approach allows for various haptic effects based on force feedback and movements of the touchscreen in the 3D space. In this section we provide several illustrative use cases, illustrated Figure 9 and in the accompany video, that we have been developed in order to show the potential of our approach.

Interacting with 3D objects: In our first use case, the user can explore and interact with virtual 3D objects. This use case relies mainly on the Shape effect. In our implementation, the user can feel the shape of several objects such as a vase or rocks.

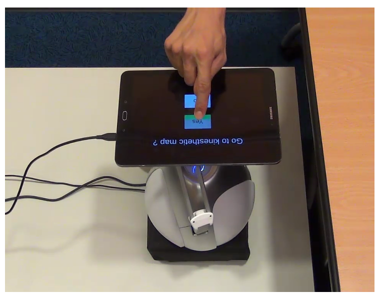
Perceiving the texture of 2D images and pictures: In our second use case, KinesTouch is used to interact with a 2D image in order to feel its texture. This use case relies mainly on the Stiffness, Sliding, and Roughness



(a) Interaction with a 3D object.



(b) Texture of a 2D image.



(c) GUI and haptic buttons.

(d) Interactive map.

Fig. 9: Illustrations of our four use cases

effects. Thanks to these effects, the user can feel the changes in: local elasticity, friction, and relief in the picture. In our implementation, a picture of a plant landscape is used, associated with several "haptic maps", similarly to the normal maps used for textures in 3D engines (here: "stiffness map", "friction map" and "roughness map").

Augmenting graphical user interface and haptic widgets: In our third use case, KinesTouch is used to enhance interaction with a Graphical User Interface made of several buttons. This simple use case relies on the Stiffness effect. In our implementation, the buttons need to be pushed at a certain depth, but have different levels of stiffness, which makes them easy or hard to validate.

Exploring Interactive maps: In our fourth use case, the user can explore the interactive map of a building. This use case relies on the Shape, Sliding, and Roughness effects. In our implementation, the 2D map (in top-view) of a big mall with three floors is used. The user can explore the layout of the shops using the finger. When stroking over stairs the user can move up or down to a different floor. The user can be attracted or repulsed from specific points/areas of interest. A vibration can also be added in presence of a targeted item.

7 Conclusion and Future Work

In this paper we have presented KinesTouch: a novel approach to enhance touchscreen interactions using kinesthetic and force feedback. With a single device, the KinesTouch provides four different types of haptics sensations: compliance, shape, fine roughness and friction. Moreover, we address a novel way of dealing with friction rendering: lateral kinesthetic feedback. We designed a proof-of-concept prototype based on the combination of a standard tablet and a consumer-grade impedance haptic device, in order to illustrate several use cases including: interacting with 3D objects or haptic widgets, exploring an interactive map, or perceiving the texture of a 2D image. We also conducted a user study on the Sliding effect to confirm that it could well induce different sliding sensations.

Creating rich haptic effects that combine the different psychophysical dimensions is probably the most promising, but also challenging following of this work. Except for vibrations that can be easily "added" to a force or kinesthetic rendering without much interferences, the compliance, shape, and friction dimensions are not trivial to associate, at least with a Falcon device that is limited in terms of dynamics and workspace. Beyond the device technical limitations, there are also conceptual limitations to combine force and position control. The proper algorithms and hardware able to tackle this issue should be explored in future.

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