FORCETAB: VISUO-HAPTIC INTERACTION WITH A FORCE-SENSITIVE ACTUATED TABLET

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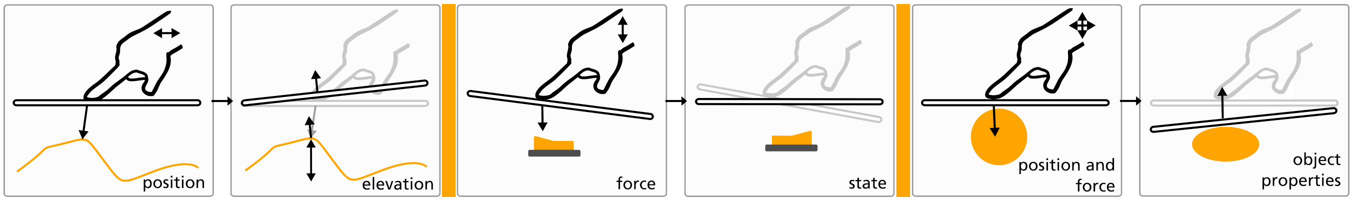

Fig. 1: Interaction concept of ForceTab (black the current state of the system and gray the previous one) (a) 2D finger position to elevation, (b) finger force to change a state and (c) continues finger position and force tracking to map physical object properties.

ABSTRACT

Enhancing touch screen interfaces through non-visual cues has been shown to improve performance. In this paper we report on a novel system that explores the usage of a force-sensitive motion-platform enhanced tablet interface to improve multi-modal interaction based on visuo-haptic instead of tactile feedback. Extending mobile touch screen with force-sensitive haptic feedback has potential to enhance performance interacting with GUIs and to improve perception of understanding relations. A user study was performed to determine the perceived recognition of different 3D shapes and the perception of different heights. Furthermore, two application scenarios are proposed to explore our proposed visuo-haptic system. The studies show the positive stance towards the feedback, as well as the found limitations related to perception of feedback.

***Index Terms*—** Touchscreen interaction, haptics, visuo-haptic feedback

1. INTRODUCTION

Touch screen interfaces have become a widespread commodity, enabling a wide variety of applications through established interaction styles. These interaction styles afford finger or pen-based interaction with a multitude of graphical user interface (GUI) elements. Often, interaction is aided by audio and simple vibro-tactile (pseudo-haptic) cues, which has been shown to enhance performance [1]. While apt for many applications, interest is growing to also explore other directions, including haptic and more advanced pseudo-haptic feedback. However, in particular the combination of haptics and touch screen interaction has not been widely studied and is still challenging. For example, sensing the shape of an underlying geometry like a button is still hard to support. In this paper, we present ForceTab, a system that explores the potential of haptic cues in touch screen interaction (see Figure 1). The system deploys a motion-platform enhanced tablet interface that has been extended with pressure sensors to sense finger pressure (see Figure 2). While related systems without pressure sensing exist, an in-depth analysis of actuated tablet interaction techniques, with and without pressure support, is lacking. In this paper, we advance beyond the state of art by presenting and validating a refined set of feedback mechanisms tailored to the abilities of the motion-platform. In particular, the pressure sensor extension allows for a wider range of haptic events to be triggered. Furthermore, in contrast to previously used 1 degree of freedom (DOF) movements [2] our approach also supports inclination, according to the position and the underlying geometry. Since most available touch screens are capacitive, capturing finger pressure is challenging unless additional techniques are applied [3]. ForceTab presents the potential of visuo-haptic devices by exploring the detection rate of different, static and dynamic, 3D geometries. To do so, we introduce a velocity guided detection approach, to determine a relationship between velocity, shapes and detection. Through a set of user studies, we report on both the low-level potential and limitations of the feedback methods to elicit shapes, and show how visuo-haptic feedback can be deployed through two application scenarios.

2. RELATED WORK

As ForceTab is a visuo-haptic device, it has some resemblance to pen-based haptic devices in general [4]. The usage of active haptic (pen) interfaces for simulation of different GUI elements is hardly studied, few examples include [5] [6]. While touchable GUI elements have been combined with tabletop touchscreens in the field of tangible interfaces[7], active feedback is complex. Moreover, in most cases haptic interaction with GUI elements has been studied using a separated screen. Forcetab also resembles shape shifting user interfaces [8] and flexible surface interaction [9] to some extent, as we also explore physical affordances and constraints in the frame of UI elements. To enhance touch screen interaction, audio [10] and tactile cues [11] have been explored, including the simulation of clicks [12] and rims [13], and aspects related to latency and perception of tactile buttons [14]. In contrast, haptic feedback for touchscreens is still largely unexplored. Some exceptions include friction screens like [15] [16] that can create the perception of force, shape, and texture on a fingertip touching a flat screen.

Our system relates to TouchMover, a large screen mounted on a large robotic arm [2] that showed potential as a large vertical mounted actuated albeit 1DOF display. Some horizontally mounted touch screen setups have also been presented, but interaction rather focused on application-driven scenarios like volumetric data exploration, or lacked an in-depth user study [17][18]. It is this research gap we target with this publication.

3. SYSTEM DESIGN AND IMPLEMENTATION

This section provides an overview of the hardware and software components.

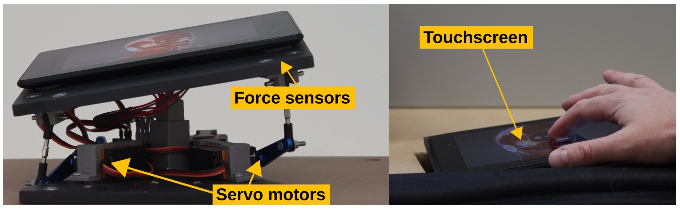

Fig. 2: Shows the hardware prototype: the force actuated touch screen lowered into a table (right). The platform is driven using 3 high speed servos and 4 force resistance senors mounted underneath the tablet (left)

3.1. Hardware

ForceTab is comprised of a motion-platform driven by three high-speed digital servos (Savox SC-1257) and four force resistance sensors (Interlink 402). This provides a 3DoF and a low latency feedback system combined with a touch sensitive display for user interaction. It enables constrained haptic feedback with screen content and supports 3 dimensional touch events. The servo motors are arranged in a equilateral triangle with a side length of 150 mm and connected to the platform using ballheads. They are operated at 6V using a external power supply, affording movement of 60 degrees in 0.07 sec, enabling the platform at high speed (average system response is 75 ms). The platform is made of fiberboard and measures 200 mm in length and 170 mm. To capture force and touch sensitivity, 4 force resistance sensors (FRS) are inserted on each edge on top of the fiberboard. Each FRS is able to sense applied force in the range of 100g-10kg. ForceTab uses an Android tablet (Asus Nexus 7), with a 7” touch screen, as the main display device. All low level introduced hardware components (servo motors and FRS) are connected to a micro-controller (Arduino Uno), that controls the servo motors and receives force events. The system is driven by a common desktop computer running a Linux system (Debian).

3.2. Implementation

A desktop computer (manager) handles time consuming tasks and the communication between the touch screen and the micro-controller. It receives touch events over WiFi (from the tablet) and force events over USB (from the micro-controller). To adjust the servo motors, signals (pulse-width modulation) are sent back to the micro-controller. A ray-based approach estimates the platform position. This is done using the finger position and an orthographic camera model. This requires a virtual camera (topview) as patterns and shapes are 3D models. An intersection point and a normal at this point is calculated using the virtual camera and the finger position. In a final step we map the estimated normal to our platform. The position of each servo is estimated using forward kinematics. Inclination mapping of the platform is a culling process, meaning that angles which are larger or smaller will mapped either to the maximum or minimum inclination. ForceTab can map heights up to 32 mm and an inclination up to 14 degrees, according to the fingers position and the underlying geometry.

Force input is computed using a distance-weighted function to linear interpolate over all four force sensors. To calibrate the force sensors, all force values are requested when ever there is no touch event and thus no motion event, so that these values are considered as new initial point. Normalizing the values within a logarithmic scale enables us to precisely capture pressure events.

The implementation supports a velocity guided mechanism to enforce users to interact within a predefined velocity range. The system can adjust velocity of an object on both, touch screen and desktop screen. This is realized using a one to one mapping from the touch screen to the main screen. Through the described configuration of hardware and implementation, ForceTab is able to support 3DoF haptic interaction, namely movement in up and down direction (height) and vertical, longitudinal inclination (gradient). In the following

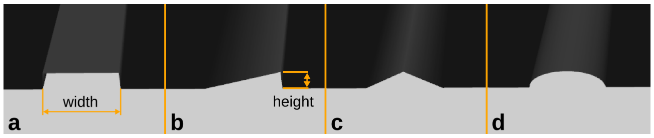

Fig. 3: Depicts the 4 patterns used for estimation vertical resolution (a) rectangular, (b) saw, (c) triangular and (d) semi-ellipse shape).

	rectangular	saw	semi-ellipse	triangular
rectangular	81%	11%	0%	8%
saw	7%	80%	4%	11%
semi-ellipse	9%	9%	35%	44%
triangular	3%	0%	61%	35%

Table 1: Detection rate and error rate of the 4 shapes. Orange cells depict the detection rate of the considered shape, additionally each column depicts the falsely detected shapes. The table indicates the confound of triangular and semi-ellipse shapes.

user study, we focus on how this feedback can be employed.

4. USER STUDY - LOW LEVEL PERCEPTION

The user study consisted of two parts: a lower-level exploratory perception driven study (force, horizontal and vertical resolution), and a study dealing with different application scenarios. In part 1 of the study, we explored if users could differentiate between different levels of pressure, and analyzed both the horizontal and vertical resolution that could be perceived by the users. This user study was performed as a within-subjects study in which 12 participants took part (age 23-38, 3 female, 9 male). Participants were seated and wore noise cancellation headphones, to block sound patterns from the servos that could provide unwanted cues. A wooden panel was placed between the tablet and the user, so users could not see the interaction device actuation (eyes-off). The position of the finger - the touch event - was mapped on a second (desktop) screen visible to the user. Here, a circle was used to indicate the finger position on the Forcetab device. After all trials, users selected the pattern they detected. The tablet was lowered into a table as such that the display was at about the same height as the table surface. The users were asked to rest the their palm onto an ergonomic wrist pad. Using this pose, users would receive feedback primarily over the finger. This avoided potential bias when the hand would need to be held in mid-air, where feedback would be partly provided over the wrist-arm lever system too. For some of the trials, a keyboard was used as input. Prior to the main study, a pilot study was performed. 6 users validated the potential of rectangular concave and convex shapes. The main outcome was that both shapes produce a similar error and detection rate: users detected concave shapes with 85 % vs. convex shapes 82 %. Subsequently in the main study we concentrated on the only one convex shapes. In the following, the term resolution refers to the detail (size and shape) of geometry that can be perceived by the user.

4.1. Force

During the study we asked the users to differentiate between 3 levels of pressure. We chose 3 levels to keep cognitive load low, while 3 levels will also provide enough DOF to explore novel force-sensitive interaction metaphors, for instance with GUIs elements. To do so, the force study employed a 2 x 3 factorial design, consisting of the factorial combination of 2 squares and 3 levels of pressure (sensitive, middle, hard). Each participant completed 12 trials in randomized order. To estimate the 3 pressure levels we asked users to push 2 squares (randomly paired levels) successively. The squares were displayed on a separate screen. Afterwards, users were asked to select the square with the higher resistance.

Results and Reflection: All users could differentiate between all 3 levels perfectly. That means, that the detection rate of the 3 force levels was 100% percent. This enables the system to response discrete to each level, for instance a button with 3 states. Moreover, ForceTab is able to map continuous movements to each level, for instance navigating through a hierarchy using 3 velocities.

4.2. Horizontal resolution

The second part of the study focused on the perceived level of detail in horizontal direction, and employed a 3 x 4 x 3 x 2 factorial design. It deployed the factorial combination of 3 exploration types (guided finger movement, dynamic patterns and free exploration), 4 shapes (see Figure 3), 3 widths (35px ≙ 2.8mm, 57.5 ≙ 4.5mm, 80px ≙ 6.5mm) and 2 velocities (3 sec and 4 sec per trial). We blocked trials into the described exploration types. Thus, each participant completed 3 x 24 trials in randomized order. Within **guided finger movement**, users were asked to follow a straight line from left to right with a specified velocity. This velocity was visualized on the desktop screen using a second circle, next to the circle indicating the finger position. In the middle of the guided path the set of different shapes with the described parameters appeared. Instead of moving the finger over the touchscreen, in **dynamic patterns** feedback passes underneath the fingertip (like a wave), while the finger is held at the same position. To activate the system the user have to move her/his finger onto a predefined rectangle at the center of the screen. The rectangle changed color to indicate the user that a shape would appear. Finally, since the previous exploration types were based on a specific velocity a third type was added. Within this exploration type the users were asked to **freely explore** the shapes for 5 seconds. After each trial the users have to choose the detected pattern. To look into learning effects, trials were separated into 2 blocks. The first block was performed with

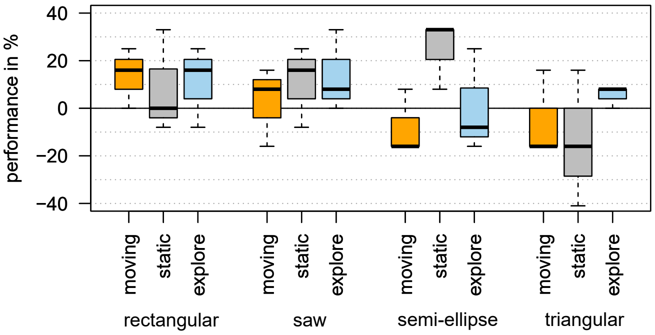

Fig. 4: Overall performance of the 3 exploration types (moving, static, explore). The graph shows the difference in detection rate including both velocities.

varying velocity, while in the second block users were asked to adjust their behavior based on their previous experiences to identify the pattern with a higher accuracy.

Results and Reflection: Table 1 shows the overall detection rate over all trials and indicates that rectangular and saw shapes were detected very well (81% and 80%). Whereas semi-ellipse and triangular shapes were detected poorly (35% and 35%). This is due to users tending to confuse semi-ellipse and triangular shapes (50% and even 64%).

Varying velocity and width of the shapes also affected the detection rate. With decreasing velocity the detection rate increased as expected. Focusing on the average performance between low vs. fast speed for the first 2 exploration types showed a higher detection rate (moving 9%, static 20%). The higher detection rate for the exploration type static is due to the fact that velocity was simulated and not user-driven. Again, the performance for rectangular and saw shapes was high when comparing the exploration types (see Figure 4).

In addition, there is an clear learning effect, as users detected rectangular and saw shapes in the second free exploration with a 12 % higher accuracy compared to the first free exploration. Due to the confused recognition of semi-ellipse and triangular shapes the performance and learning effect analysis is not indicative. It only shows that within the given interaction metaphors and velocity users can differentiate between 3 different shapes.

Furthermore, we evaluated 3 levels of width (35px, 57.5px, 80px). As assumed, the larger the width the higher the detection rate (see Figure 5). The detection rate at 35px for rectangular and saw shapes was 76% and 63% respectively. The average detection rate increased with increasing width (57.5px detection rate 79% (rectangular) and 85% (saw) and at 80px detection rate 86% (rectangular) and 89% (saw)). While the detection rate of semi-ellipse also increased with increasing width, the detection rate was still too low. Due to the confusion of the shapes c and d the analysis of triangular and semi-ellipse shapes is not indicative. The study of

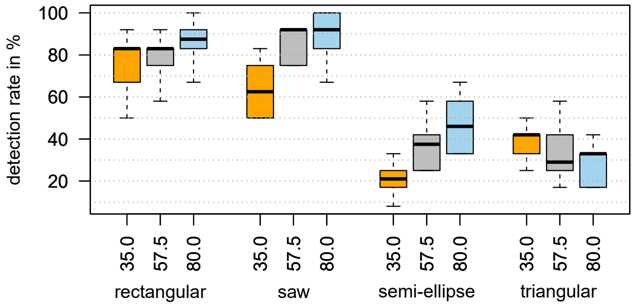

Fig. 5: Box plots showing the detection rate per width (35px, 57.5px, 80px) for each shape and overall interaction metaphors.

perceived horizontal resolution showed several important outcomes. First, the impact of the shapes' properties, like form, are an essential issue when estimating the perceived detail and especially designing applications for ForceTab and similar devices. Distinct properties, such as strong discontinuity, can be well recognized by the almost all users. Participants reported they are able to observe particular properties in the shapes. Whereas similar shapes with no unique features are hard to distinguish.

Second, there is a correlation between velocity and width, showing that shapes with a width smaller than 57.5px ($\hat{=}$ 4.5mm) are not feasible for finger interaction. To increase the detection rate we would recommend an even larger width (80px $\hat{=}$ 6.5mm).

Lastly, as users habitually interact with touch screens in a visual guided way - meaning that visual elements are the main factor controlling finger position and velocity - users have to adapt to the novel interaction properties. This means that when adding haptic cues to touch screens users should be motivated to adapt finger velocity to the underlying geometry (fine shapes require slow movements and coarse shapes allow faster movements). A finger velocity at around 0.025 $\frac{m}{s}$ has gained good results for the proposed scenarios.

4.3. Vertical resolution

The last session of the lower-level perception part of the study looked at the estimation of the perceived vertical resolution, and employed a 4 x 3 x 2 factorial design. The study deployed the factorial combination of 4 elevations (varying between 3mm, 5mm, 7mm, 9mm) and 3 shapes (diameter/side length 35mm, a box shape, a pyramid shape and a bump (Gaussian) shape). Each user completed 18 trials in randomized order. In contrast to our prior study we enabled inclination. Users were asked to find the highest point on the tablet. Again, a circular shape on the second screen indicated the finger position on the tablet while no additional information was displayed. In each trial, 2 elevations with different heights but same shape were mapped on the tablet with a random position but no overlaps - equal heights were not allowed. If the user has found

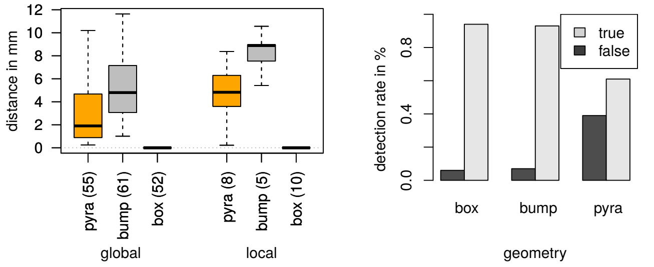

Fig. 6: Distance to the global and local maximum for each shape, frequency is listed in brackets (left). Detection rate of each shape is depicted in the bar plot (right).

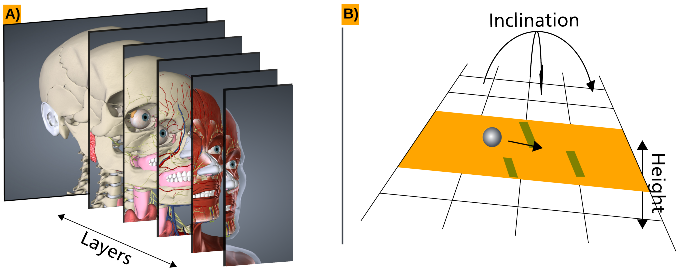

Fig. 7: Depicts two possible application scenarios. A layered image stack of a anatomy data set (left) and a physical plane with gravity (right).

a maximum the distance to each maximum local and global was recorded. Thereafter users were asked which shape they recognized.

Results and Reflection Users were able to find the global maximum with a accuracy of 87%, which indicates that even small differences could be perceived by the users. Boxes were either found or not, but for pyramids and bumps we can clearly determine the distance to the maximum. Figure 6 depicts this distance to the global and local maximum grouped by the 3 shapes. The median distance to the global maximum for pyramid shapes was 2mm and for bump shapes 4.8mm. Looking closer to the relative differences in heights (2mm, 4mm and 6mm), in average users were able to find the global maximum with an accuracy of 78%, 90% and 90% for each height, respectively. Furthermore, Figure 6 shows the detection rate of the 3 shapes, which was high for most but not all shapes (box 94%, bump 93% and pyramid 61%).

The results show that the proposed system is able to generate different heights/elevations that can be well perceived by the users. As expected, users have more difficulties differentiating between smaller differences than with larger ones. As the top of pyramid shapes was detected more precisely than the top of bump shapes, we expected that the detection rate of pyramid shapes should be equally or even higher compared than the other two shapes: we thought a user might draw conclusions from the shapes top, which was actually not the case. However, finding the top of pyramids was underlined by feeling a peak at the maximum. Pyramids were often perceived as bumps (34%) but not the other way round (4%). However, in general users commented that inclination of the actuated platform helped to detect the shapes.

5. APPLICATION SCENARIOS

Last, we combined pressure, position and visual feedback within two different application scenarios(see Figure 7). In the **level of detail viewer** scenario, we visualized a layered image stack of a anatomy data set. The position/height of the tablet indicated the different layers. From the muscles, over veins to the skeleton, all levels were accessible through different finger pressure. In addition to the vertical layers, each layer could also be accessed individually for additional layer information. As such, the system employed 2 dimensions of information, one in vertical direction (layered data) and the other around the pitch axis (additional information). In the **physical interaction plane** scenario the tablet acted like a physical plane. Based on the angle of inclination, the elements displayed on the tablet moved to the deepest point of the plane, based on the friction and gravity parameter of each object. Small obstacles were integrated to show collision detection. We designed two interaction metaphors to access either different levels of detail (first scenario) or to manipulate the physical plane (second scenario). A force-based metaphor (finger pressure) and a position based metaphor (finger position) was implemented to control the touch screens position.

Users explored each scenario for at least 90 seconds. Thereafter, the users were asked to answer a set of questions (7 point Likert scale, strongly disagree (7)). Users rated state based feedback well in both the layered image viewer (avg 2.6/sd 1.2) and physical plane (avg 1.8/sd 0.7). In addition, the novel force based metaphors (avg 2.8/sd 1.4) gained almost the same result as position based metaphors (avg 2.7/sd 1.6). The overall satisfaction with the system was rated with (avg 2.2/sd 1.1).

6. CONCLUSION AND FUTURE WORK

Within this paper we looked into the pressure levels, as well as vertical and horizontal resolution users can perceive while using our actuated platform. This understanding is crucial to design and develop real applications scenarios. Interacting with mobile actuated displays is new to almost all users. In our results, we identified system constraints as depicted by the boundaries of the system feedback, while also highlighting user's perceptual capabilities in frame of the provided feedback range. While not necessary for many GUI element interactions, as a next step it would still be beneficial to perform a just-noticeable difference experiment to further study finer-grained feedback levels. We presented results of feasible mappings that need to be adjusted to particular applications. Our results create an understanding of the possibility and limitations of comparable platforms such as presented by Kim et al. [17]. The system by Sinclair et al. [2] showed a better detection rate in 1DOF, but in comparison to our study, users were able to see the visual display device which strongly supports the identification of shapes. Another novel aspect is the introduced force-sensing method. An actuated force-sensitive visuo-haptic platform can enable a set of novel application scenarios and interaction metaphors, which we partly explored in the application section. For instance, in education ForceTab can enhance knowledge transfer: data can become "tangible" to support users to understand relations and conditions better. Based on users' feedback, we will extend ForceTab to a broader range of multimodal feedback, in particular vibrotactile and audio feedback. Both can help to further enhance perceptual issues of mapped geometry. For example, tactile and audio cues might enhance the perception of edges and borders, which is an issue of the current system. Since we analyzed perceived resolution and proposed two scenarios of state based interaction, in the future we would like to focus on the third feasible interaction component: continuous tracking of force and position to explore additional object properties, like stiffness and surface texture.

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