ForceStamps: Fiducial Markers for Pressure-sensitive Touch Surfaces to Support Rapid Prototyping of Physical Control Interfaces

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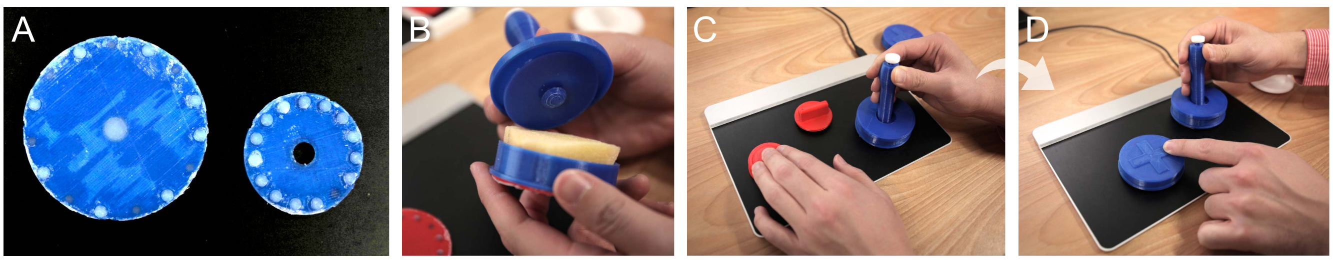

Figure 1: ForceStamps workflow. A) ForceStamp fiducials can be easily fabricated with off-the-shelf 3D printers. They are recognized on pressure-sensitive touch surfaces owing to their dedicated footprints. B) Designers can transform ForceStamps into different physical controls by attaching mechanisms to ForceStamps. C) Designers can instantly create an interface layout by placing the controls on the touch surface, D) and can reconfigure the interface layout instantly by swapping the controls.

ABSTRACT

We present *ForceStamps*, fiducial markers for supporting rapid prototyping of physical control interfaces on pressure-sensitive touch surfaces. We investigate marker design options for supporting various physical controls, with focusing on creating dedicated footprints and maintaining the structural stability. ForceStamps can be persistently tracked on surfaces along with the force information and other attributes. Designers without knowledge of electronics can rapidly prototype physical controls by attaching mechanisms to ForceStamps, while manipulating the haptic feedback with buffer materials. The created control widgets can be spatially configured on the touch surface to make an interface layout. We showcase a variety of example controls created with ForceStamps. In addition, we report on our analysis of a two-day musical instrument design workshop to explore the affordances of ForceStamps for making novel instruments with diverse interaction designs.

TEI '20, February 9–12, 2020, Sydney, NSW, Australia

ACM ISBN 978-1-4503-6107-1/20/02…$15.00
https://doi.org/10.1145/3374920.3374924

CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**.

KEYWORDS

Fiducial markers, physical controls, tangible user interfaces, pressure sensing

ACM Reference Format:
Changyo Han, Katsufumi Matsui, and Takeshi Naemura. 2020. ForceStamps: Fiducial Markers for Pressure-sensitive Touch Surfaces to Support Rapid Prototyping of Physical Control Interfaces. In *Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '20), February 9–12, 2020, Sydney, NSW, Australia.* ACM, New York, NY, USA, 13 pages. https://doi.org/10.1145/3374920.3374924

1 INTRODUCTION

Recent advances in affordable digital fabrication tools, represented by 3D printers, enable designers and makers to make a variety of *personalized* geometric shapes quickly. However, the produced prototypes are essentially passive and most of digital fabrication machines cannot create immediately functional interfaces after fabrication. Embedded electronics platforms such as *Arduino*[1] are necessary tools for instrumentating static physical prototypes and attributing interactivity to them. Although embedded electronics enable designers to make *solid* physical interfaces, going through the iterative design process with such platforms is time consuming.

On the other hand, there are an overwhelming number of capacitive multi-touch surfaces around us (e.g., smartphones, tablets, trackpads). Even though the touch surfaces themselves offers intuitive touch interactions, it is possible to further extend flat surfaces to *graspable* tangible user interfaces by placing specially designed physical tokens on them [4, 15, 20, 31, 39, 40]. Layout of such tangible user interfaces can be reconfigured instantly without wired electronics if the surface can identify the tangibles, for example, by using fiducial markers [6, 8, 18, 49]. However, it is difficult to implement a force-sensing capability to such tangibles. Embedding force sensing electronic components such as force-sensing resistors in tangibles [12, 15, 46] or printing conductive materials with flexible materials to change internal capacitance [40] are feasible ways to implement such abilities. Though, all of these approaches require relatively complicated fabrication tools (dual extruder 3D printers) or embedded electronics and batteries. We argue that physical interface prototyping should be performed with less time and effort.

In this paper, we present *ForceStamps*, fiducial markers to facilitate physical interface prototyping on pressure-sensitive touch surfaces. ForceStamps can be fabricated with a commercial 3D printer at a low cost (Figure 1A) and can be recognized on pressure-sensitive touch surfaces. Each ForceStamp marker has dedicated footprints composed of several protrusions (we will refer to them as "pins" in this paper) representing a binary code. While tracking the ForceStamps on touch surfaces, we can monitor the applied force to them. By attaching soft buffer materials on ForceStamps, Designers and makers can manipulate the haptic feedback (relationship between the displacement and the force) whereas providing a room for tilt movements for creating a diverse physical controls. (Figure 1B). ForceStamps enable us to prototype instantly reconfigurable physical interfaces on touch surfaces (Figure 1C, D).

As our work focuses on designing fiducial markers for pressure-sensitive touch surfaces, this paper shares several features with the prior work *Geckos* [25]. Geckos presented tangible objects that can be tracked on pressure-sensitive touch surfaces with unique contact point constellations. It is also presented that various interactions such as continuous pressure input, and approximation of the single-point touch position on tangible objects. However, the interaction examples were limited to thin, flat tangibles. Also, since the users

[1]https://www.arduino.cc/

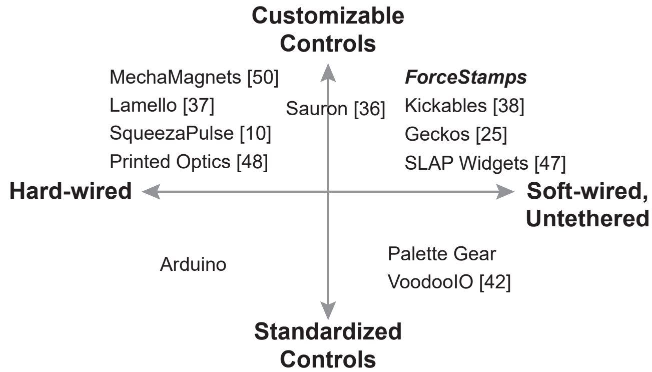

Figure 2: Comparison of related systems from the viewpoint of physical interface prototyping

design the constellation of the footprints, the markers do not have dedicated IDs. This may induce duplicate between with previously registered markers. Furthermore, there had been no discussion about the structural stability of tangible objects with biased footprints.

In this paper, we contribute to the following technical points:

- Marker geometry design for attributing dedicated IDs to fiducial markers while supporting a wide range of movements. (Figure 5).
- Exploration of marker pin shapes and materials for structural stability and effective force transmission (Figure 7).
- Technical evaluation of single-touch point angle approximation on the markers (Figure 10).
- Demonstration of diverse physical control examples achieved by designing control mechanism with buffer materials (Figure 13).
- A workshop study that explores the affordances of ForceStamps in designing electronic musical instruments (Figure 16).

2 RELATED WORK

Rapid Prototyping of Physical Interfaces

We compared the related systems and ForceStamps in the viewpoint of physical interface prototyping as shown in Figure 2. In the field of human-computer interaction, *VoodooIO* envisioned that *malleable* control structure could enable users to instantly deploy and adapt controls to satisfy their ergonomic preferences and control requirements [42]. For a commercial product, reconfigurable modular platforms like *Palette Gears*[2] provide a few control primitives (buttons, knobs, sliders) to iterate over different interface layouts. However, such platforms merely provide standardized modules, which hinders exploring the haptic feedback of

[2]https://palettegear.com/

diverse physical controls. Several approaches aim to support fabricating diverse physical controls with digital fabrication techniques. *Printed Optics* [48] create distinct physical inputs by 3D printing optical fibers to manipulate the light paths. *Lamello* and [37] *SqueezaPulse* [10] analyze the audio signals synthesized by 3D-printed structures to obtain the movement of physical inputs. *MechaMagnets* [50] provides a design workflow to design both haptic feedback and input capabilities with 3D-printed mechanisms and permanent magnets. Though, the above systems require physically tethered wires and electronics to sense the state of physical interfaces. To overcome such limitations, *Sauron* [36] introduces internal camera and vision-based approach to sense the state of physical controls that has embedded fiducial markers. While *Pineal* [24] and *Acoustruments* [23] aimed for attributing interactivity to fabricated objects by embedding mobile devices (e.g., smartphones), but the size is restricted by the dimension of the devices. In ForceStamps, we provide untethered physical controls which could be reconfigured on the touch surface. Thus, ForceStamps lowers the barrier in designing physical control prototypes since the users need not to have knowledge of electronics.

Identifying Tangibles on Touch Surfaces

Distinguishing objects on surfaces enables us to design distinct interactions to different tangibles [16]. From a physical interface prototyping perspective, this feature allows us to change the interface layout on the fly. For the tabletop systems which uses direct illumination (DI) or frustrated total internal reflection (FTIR) technology, reflective markers are often used [1, 17, 22, 47]. Another way is to embed wireless communication modules into tangibles for allowing the system to confirm the presence of an object [30, 44, 49]. Passive NFC tags can also be used to attribute dedicated IDs to objects [43]. For capacitive multi-touch surfaces, capacitance tags [31] are one of the promising candidates since they are passive and relatively easy to fabricate. Unique footprints composed of conductive materials and non-conductive materials enable the touch sensor to classify different objects [6, 8, 15, 45, 49]. Others investigated utilizing multiple magnets to create unique magnetic patterns to recognize objects [26, 27]. Some groups have investigated methods to recognize tangibles on pressure-sensitive touch surfaces with footprints of everyday artifacts [13], magnet-augmented tangibles which can work on vertical walls [25], or 3D-printed markers with many protrusions [9]. In ForceStamps, we aim to investigate robust and dedicated fiducial marker design for pressure-sensitive touch surfaces considering various user interactions.

Pressure Sensing through Objects

Pressure information can be used to handle continuous parameters with precision, such as scroll speeds, drawing line thickness, or multi-level button presses [32]. On the other hand, introducing a 2D pressure sensor array instead of one or several pressure sensors makes it possible to measure entire pressure changes on the plane. Such sensors can be made with low-cost fabrication techniques [5, 7, 29, 33, 34] or are readily available as off-the-shelf products[3]. Also, sensing pressure through tangible objects brings another design possibility to the interaction. *Geckos* [25] presented a system which uses magnets to manipulate haptic feedback while changing the footprint of the tangibles. In *GravitySpace* [3] and *Kickables* [38], the authors created objects that propagates pressure to a pressure-sensing floor. *FDSense* [14] demonstrated that it is possible to estimate Young's modulus of a contacting material to diversify interactions depending on the material stiffness. *Geckos* presented several force interaction examples, they are limited to flat and thin tangibles. This paper mainly aims to find the design possibilities of 2D pressure images for *graspable* 2.5D tangible user interfaces. We further demonstrate how embedding soft materials on ForceStamps can improve operability with several physical interface examples.

3 FORCESTAMPS

In this section, we introduce both the hardware and software implementation of ForceStamps. We first derived available ForceStamp attributes as shown in Figure 3. ForceStamps have six types of attributes which can be used to identify or sense the movement of physical controls. Given these considerations, we design the geometry of the ForceStamp marker, aiming to guarantee the dedicated ID and the structural stability. After describing the recognition process of ForceStamps, we investigate the size constraint and behavior with different pin shapes and material combinations with technical evaluations.

Design Challenges

Figure 4 shows design challenges for fiducials on pressure-sensitive touch surfaces. As stated in Geckos, we can make a combination of contact points to utilize it as an unique footprint (ID) [25], but as shown in Figure 4A, sometimes such footprint may look similar to previously registered footprints and cannot be distinguished from them. To guarantee the uniqueness of an ID, it is desirable to computationally generate the constellation of footprints. In addition, the structural stability of the marker could be destroyed if the marker has biased pin arrangement as illustrated in the left of Figure 4B. The markers can stand stable when the force is applied to

[3]Sensel Morph, https://sensel.com/pages/the-sensel-morph

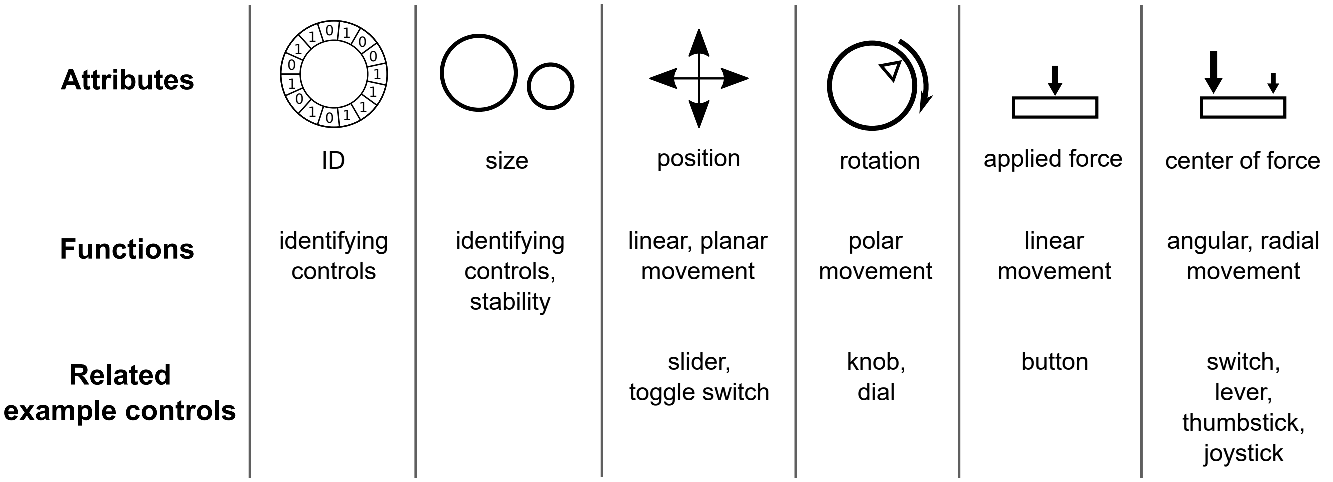

Figure 3: ForceStamp attributes, their functions and related example controls.

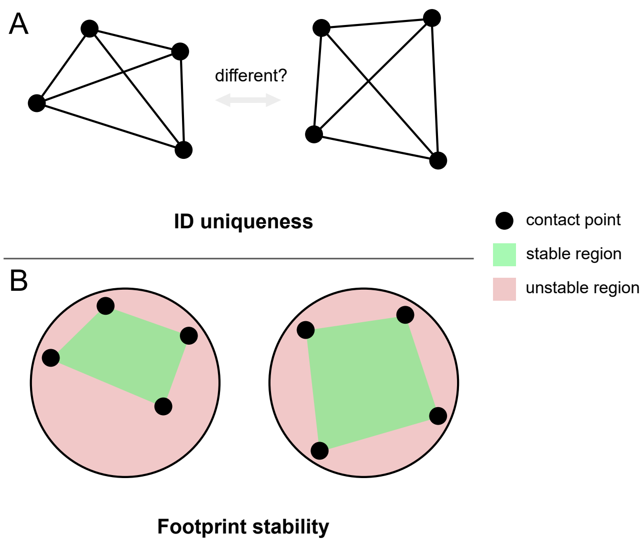

Figure 4: Design challenges of fiducials on pressure-sensitive touch surfaces. A) Guaranteeing ID uniqueness for point constellations and B) maintaining structural stability of the marker.

roughly the green region (inside of the polygon which is composed of the marker pins), but the marker collapses if we push the red region (outside of the polygon). we can increase the structural stability by moving the pins near to the border of the marker, and distributing them. Taking these factors into account, we investigate the design options for the geometry of ForceStamps.

Geometry

We first determine the geometric constraint of the marker. We aimed to design a general geometry that could fulfill all required functions as depicted in Figure 3. Among them, polar, angular and radial movements require the markers to be stay stable even if there is a offset in the center of force. For

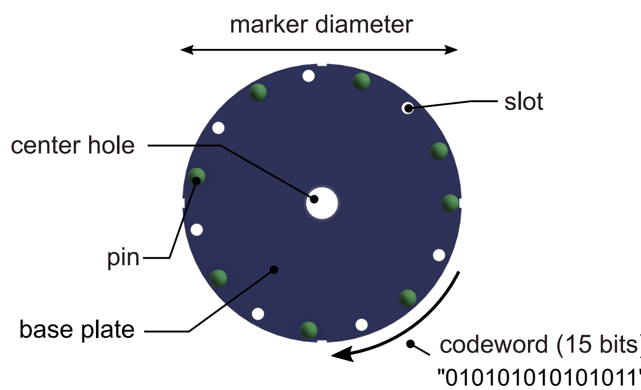

Figure 5: ForceStamp marker geometry. A n-bit binary code is embedded into the slots placed along the circumference.

example, if we design a joystick with the marker, it should be tilted to any direction without collapsing. As explored in previous studies, minimizing the contact area to the sensor surface helps to achieve a dedicated pressure image [9, 25]. *Random dot markers* [41] can be a possible candidate since it exploits randomly scattered dots to set up a unique ID. However, since it is not guaranteed that the dots are evenly distributed, it might affect the operability of the physical controls. Accordingly, We adopted the design strategy discussed in *RUNE-Tag* [2]: a circular marker for AR applications. A ForceStamp marker is composed of n slots arranged on the circumference of a circular baseplate as depicted in Figure 5. For an empty slot, we can allocate a pin to represent binary bit '1'. Figure 5 shows an example of embedding a 15-bit binary code (010101010101011) to represent a dedicated ID. We can quickly determine the center of marker since the pins are only in the perimeter of a circle. Also, the structural stability of the marker can be managed by choosing proper code patterns which will be discussed in Marker Size and Number of IDs section.

Hardware

For a pressure-sensitive touch surface, we selected the *Sensel Morph* touchpad since it is an off-the-shelf product and the manufacturer provides an API to access raw pressure images from the device[4]. The *Sensel Morph* has a 2D array of 19,425 (185 columns ×105 rows, 1.25 mm pixel spacing, 240 mm ×169.5 mm) force sensors [35]. Each touch point has a dynamic range of 30,000 levels and can measure forces from 0.005 kgf to 5 kgf. At the highest resolution operation mode, the touchpad can read the input on all pressure sensors at up to 125 Hz.

Marker Detection and Recognition

An abstracted process of detecting and recognizing ForceStamps is described in Algorithm 1. To find the marker footprints, we first perform local peak detection for every blob appear in the captured pressure image. The peaks are persistently tracked until they disappear from the pressure image. For marker detection, only the peaks appeared in less than one second are used to prevent detecting false positives and reduce computational complexity. Then, for predefined marker radii, we find circle candidates for a combination of a pair of peaks. If the counting of the peaks on the circle periphery is over threshold, the peaks are assigned to a marker and the marker is registered. At the time of marker registration, we do not determine the marker ID since some pins may not touch the surface. When a force over a certain threshold is applied and the center of force is below a threshold (properly *stamped* onto the surface), we recognize and determine the marker ID. To recognize the ID, we count the peaks in the slots to obtain the binary code, then we compare the decoded codeword with the predefined code table to determine the ID. Once the ID is determined, it is kept until all the contacts assigned to the marker disappear. Also, the marker object continuously tracks and adds the assigned peaks in the marker region so the marker to persistently recognized. If the code is rotationally asymmetric, the absolute orientation of the marker could also be derived by comparing the bit shift to the reference codeword. For markers those have rotational symmetry, we can still calculate the relative rotation with the peak positions in the previous frame. The applied force can be simply calculated by summing up all pixel values in the marker area. To derive the center of force, we calculate the weighted center of gravity (force) as shown in Equation 1:

$$(x_{cof}, y_{cof}) = \left(\frac{\sum_{i=1}^{M} m_{xi}x_i}{N}, \frac{\sum_{i=1}^{M} m_{yi}y_i}{N}\right), \qquad (1)$$

[4]https://guide.sensel.com/api/

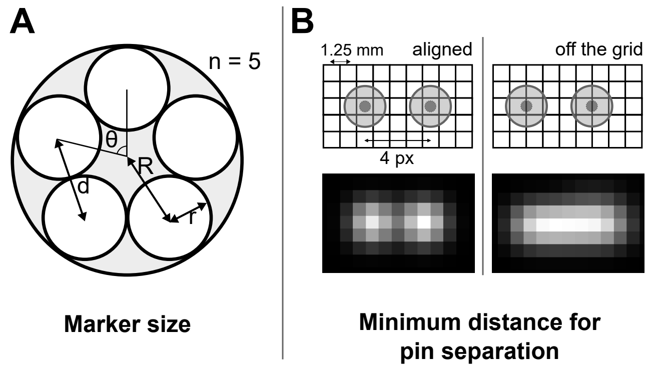

Figure 6: Constraints for determining marker size. A) Minimum size of the marker when $n = 5$. B) Resulting pressure images of two adjacent pins when they are aligned with the sensor grid (left), and off the grid (right)

where M is the size of the marker region, m_{xi} and m_{yi} are projected pixel values to each axis, x_i and y_i are coordinates, and N is the sum of all pixels in the area.

Algorithm 1 ForceStamps

```
MarkerRaii ← [r1, r2, ...]
while true do
    Markers ← []
    img ← ReadPressureImage()
    peaks ← GetPeaks(img)
    for r in MarkerRadii do
        centers ← FindCircles(img, peaks, r)
        for cnt in centers do
            isVal ← ValidateMarker(cnt, r)
            if isVal then Markers.add(Marker(peaks))
    for mkr in Markers do
        mkr.RecognizeID(mkr.threshold)
        mkr.GetPosition(mkr.peaks)
        mkr.CalculateRotation(mkr.peaks)
        mkr.CalculateForce(mkr.img)
        mkr.CalculateForceCenter(mkr.img)
```

Marker Size and Number of IDs

As the area of the touch surface is limited, it is helpful to know the size constraint of the markers. The minimum size of the marker is related to the number of slots and the grid resolution of the touch surface. An example of marker design for $n = 5$ is illustrated in Figure 6A. Assuming that pins do not intersect with each other, the minimum diameter of the marker is expressed as

$$2(r + R) = 2\left(r + \frac{d}{2sin\frac{\pi}{n}}\right). \qquad (2)$$

In addition, the diameter of the pins should be smaller than the distance between adjacent pins ($2r \leq d$).

Next, we tested the performance of the touchpad in separating two adjacent contact points. We fabricated the pins with a fused deposition modeling (FDM) 3D printer using a flexible filament[5]. The tip diameter of the pins kept smaller than sensor grid pitch (< 1.25 mm). We varied the distance between two pins, and precisely placed the pins onto the touch surface and applied 1 N of force. Figure 6B shows when the distance was 4 pixels (5 mm). We can see the two distinct peaks when the pins are aligned with the sensor grid. However, when the pins are off the grid, they are not separate due to the lack of grid resolution. This is due to the interpolating behavior of the touchpad, which offers relatively lower grid resolution than positional resolution [34]. Hence, we decided to keep the two pins to be at least 5 pixels apart (6.25 mm). We used this distance to define the minimum size of the markers.

Table 1: Number of IDs and minimum size of markers with different number of slots

n	8	10	12	15
unique codes (no. ID)	36	108	352	2192
at least three ones (no. ID)	30	101	344	2183
asymmetric (no. ID)	26	94	329	2174
no repeating zeros (no. ID)	5	11	25	90
adj. pin angle θ (deg)	45	36	30	24
min marker diameter (mm)	22.58	26.47	30.39	36.31

We calculated the number of available IDs and the minimum size of markers with different number of slots as described in Table 1. First, the number of unique codes are restricted by cyclic symmetry of the marker. After that, we exclude codes that have less than three ones since they do not stay stable on the touch surface. To obtain absolute orientation of the marker, we further exclude rotational symmetric codes. As the structural stability of the marker is affected by the area of polygon composed of point constellations, we attempt to restrict the frequency of zeros in the code. For instance, when we exclude the codes which has at least two repeating zeros, there are 90 unique IDs when the n is 15. Then the minimum diameter of the marker is determined as 36.31 mm.

Pin Shape and Material for Force Transmission

The force measured by the touch surface is affected by both the applied force and the contact area [14]. By changing the stiffness and geometry of the marker pins, we can alter the force transmission characteristics of the markers. To investigate the impact of geometry and materials on force transmission, we conducted an experiment with nine material and geometry pairs as shown in Figure 7. The markers

[5]*Ninjaflex*, https://ninjatek.com/tech-specs/

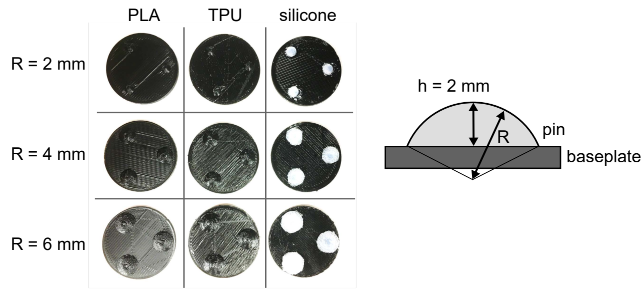

Figure 7: Marker samples for investigating the force transmission characteristic of various pin shape and material combinations

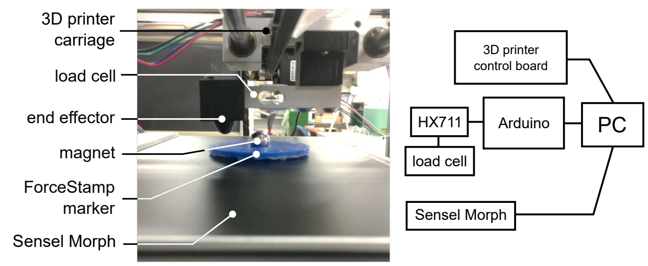

Figure 8: Experimental setup to measure applied force to the ForceStamp at various points.

Table 2: The slope coefficient and the R^2 of the linear fits.

slope / R^2	R = 2 mm	R = 4 mm	R = 6 mm
PLA	0.49 / 0.88	0.49 / 0.92	0.23 / 0.76
TPU	0.46 / 0.72	0.91 / 0.83	1.14 / 0.95
silicone	2.66 / 0.98	3.25 / 0.99	3.65 / 0.98

had three pins in three slots and the diameter of the marker was 30 mm. The radius of the circle (R) was 10 mm. For pin geometries, we kept the height of the pins as 2 mm while changing the curvature radii of the pins as 2 mm, 4 mm and 6 mm. We fabricated the ForceStamp markers with three different combinations of materials with 3D printing (an FDM machine) and casting (for silicones). While maintaining the stiffness of the baseplate (PLA, Shore hardness 95D), we changed the hardness of the contact pin with PLA (Shore hardness 95D), TPU (Shore hardness 85A) and cast silicone (Shore hardness 5A).

We constructed a custom apparatus for applying precise amount of force to markers at various touch points as shown in Figure 8. The *Sensel Morph* touchpad was placed on the vertically moving platform of the 3D printer. We attached a load cell (SC133) equipped with a 3D-printed round-shaped end effector (*Ninjaflex TPU*) to the 3D printer XY carriage. The load cell was precisely calibrated using a digital weighing scale. The analog voltage of the loadcell is amplified by HX711 amplifier module and transferred to a PC via *Arduino UNO*. The *Sensel Morph*, the 3D printer, and the load cell

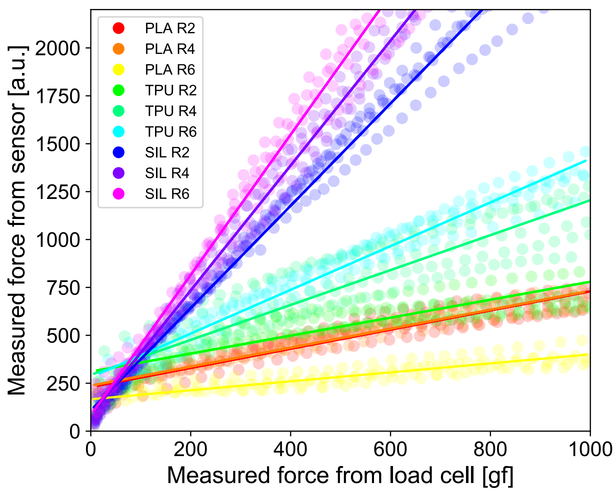

Figure 9: Measured force transmission characteristics of different material combinations.

Table 3: The mean error and the standard deviation (SD) of the approximated touchpoint angles.

	ID: 1	ID: 40	ID: 69	ID: 90
Mean error (°)	6.11	7.42	7.78	6.67
SD (°)	6.88	8.48	8.79	8.11

are simultaneously monitored and controlled via a tethered laptop.

The end effector gradually pressed the center of the markers at five different positions of the touchpad, while measuring the applied force from the load cell. Figure 9 shows relationship between the applied force and the touchpad-measured force and Table 2 shows the slope coefficient and R^2 of the linear fits. The measured values are sum of all pixel values in the pressure image retrieved via Sensel Morph API. Since the measured force of a pressure-sensitive surface is a coupling of the force and the contact area [28], we can observe from the results that the measured force increases along with the pin material becomes soft, because soft materials deform more so to increase the contact area. Similarly, for the soft materials (TPU and silicone), the slope coefficients increased as the curvature radius increased. However, for the hard material (PLA), the slope efficient did not show positive regression with the curvature radius. In this case, since the hard material did not deform enough, the contact area had less relationship between the curvature radius.

Accuracy of Touch Point Approximation

To support the feasibility of utilizing the center of force as directional tilt inputs, we investigated the accuracy of touch point (angle) approximation. For the measurement,

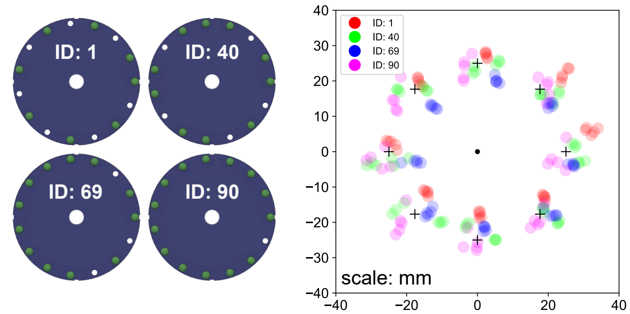

Figure 10: Geometry of the tested markers (left) and the scatterplot of the measured center of force.

we fabricated a set of markers with 3D printing and silicone casting. The diameter of the markers was 60 mm, and the radius of the circle (R) was 27.5 mm. The pins were made of cast silicone and the radius and height of the pins were both 2 mm. We set the number of slots as 15, and restricted the pin distribution not to have repeating zeros as stated in the Table 1. From the resulting 90 IDs, we randomly selected four patterns (Figure 10) with different number of pins: 8, 10, 12, 14 pins for ID 1, 40, 69 and 90, respectively. We fixed each marker on the surface by putting a sphere magnet onto the center hole of the markers, while putting a steel sheet underneath the surface as shown in Figure 8, which applied approximately 1 N (100 gf) of force to the marker. We moved the end effector over the marker and pressed eight points 25 mm away from the center five times with approximately 1 N of force. The angle of the touch point from the center was increment by 45°. We controlled the Z-axis movement speed (0.08 mm/s) to be slow enough to let the force measurement from the load cell (about 10 Hz) to follow the change of the applied force.

Figure 10 shows the scatterplot of the touchpoints calculated from the Equation 1. Since the center of force is normalized with the total force, we scaled the magnitude of the center of force vectors by ratio of the touch point offset (25 mm) and the mean magnitude. As shown in the Table 3, all mean errors and standard deviations kept less than 10°, which is appropriate enough for distinguishing eight-directional movements. There were also no noticeable differences between the markers, which implies that there was no critical bias in pin arrangement with the proposed geometries.

4 DESIGNING WITH FORCESTAMP

In this section, we discuss the feasibility of ForceStamps for designing physical interface prototypes. First, we introduce the workflow with a variety of example interfaces fabricated with 3D printers. Then, we introduce an example scenario of using those controls for playing video games. Finally, we

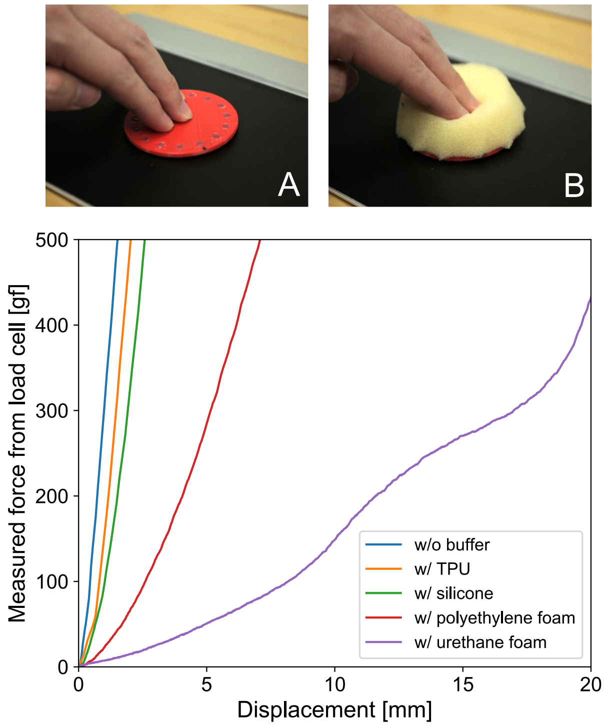

Figure 11: Attaching soft buffer materials on the marker changes both the perceived force and measured force against the displacement. A) Without buffer materials. B) With an urethane foam sponge.

demonstrate diverse interaction designs for novel musical instruments from a workshop study.

Haptic Feedback Manipulation with Buffer Materials

When making a physical control with ForceStamps, we can attach soft buffer materials on the marker to design the haptic feedback. For example, if we put a foam sponge on a bare marker as shown in Figure 11B, the transmitted force to the surface is suppressed since the sponge should be compressed to transmit enough force. The buffer material does not only change the amount of displacement but also alters the haptic response according to the resilience of the material. As Kim et al. pointed out, we measured the force-displacement curves with various buffer materials since they are useful for quantifying the haptic feedback [21]. We tested out four different buffer materials to explore the ability of each material to adjust the force-displacement curve: A 3D-printed TPU block, a cast silicone, a polyethylene foam, and an urethane foam. The dimensions of the buffer material blocks was 25 mm × 25 mm × 20 mm. Curves shown in Figure 11 implies that we can gain more displacement at a certain amount of applied force, which is useful for obtaining enough room for tilting or continuous force inputs.

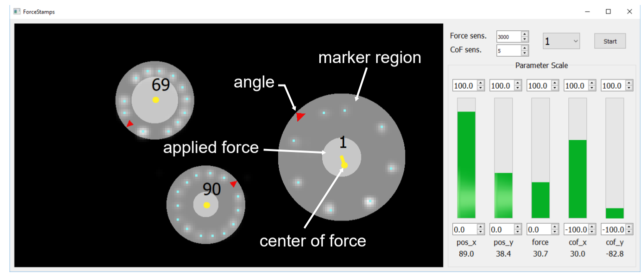

Figure 12: A GUI for monitoring the ForceStamp attributes.

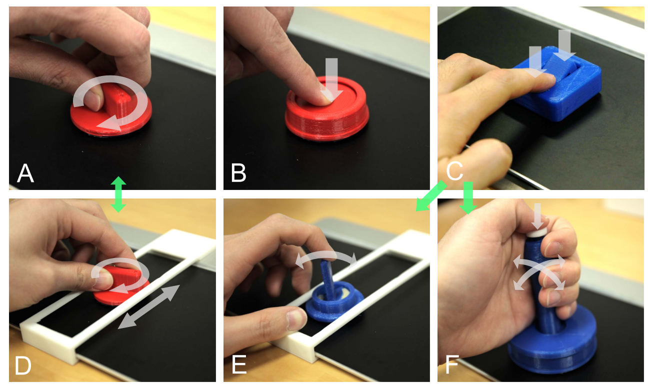

Figure 13: Example of physical interfaces designed with ForceStamp: A) Control knob, B) Push button, C) Rocker switch, D) Vertical slider with a control knob, E) Lever, and F) Joystick with a fire button.

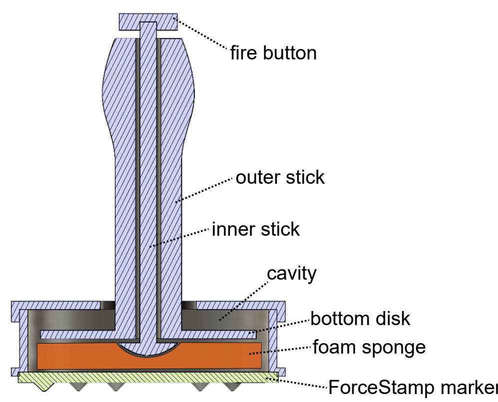

Figure 14: A cross sectional view of the joystick with a top fire button.

Workflow and Interface Examples

We designed a GUI for monitoring the ForceStamps attributes as shown in Figure 12 [6]. It visualizes abstraction of parameters over the raw pressure image. The range of the parameters can be scaled for different marker IDs and the they can be sent to other applications. The messages are formatted in the TUIO 2.0 [19] and sent via *open sound control (OSC)*.

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[6] Available at https://github.com/hanchangyo/forcestamps

Designers can design specific geometries and mechanisms for attachments to change the behavior of ForceStamps. For example, attaching an empty cavity on a ForceStamp marker and filling it with a soft material changes the haptic feedback to the vertical direction. Also, by adding spatial constraints to the touch surface or the attachments, designers can attribute different functionality to the prototype controls and rapidly iterate over designs with digital fabrication tools. Of course, designers can test out different interface layouts by placing the controls on the touchpad.

We showcase several examples of physical interfaces in Figure 13.

A) Control knob: Equipped with a handle for more natural turn and conversion of rotary motion to a continuous input.

B) Push button: A simple push button which performs continuous force input. The cavity underneath the button is filled with a foam sponge for resiliency.

C) Rocker switch: As the user presses the either end of the button the center of force changes. The distinct button press can be estimated with the shift in the center of force and the state of the button can be recorded as the button has a locking mechanism.

D) Vertical slider with a control knob: By giving spatial constraints to the tangential direction with a linear guide rail, the control knob transforms into a slider while keeping the rotational function available. We can create a unique slider control which could be rotated while sliding.

E) Lever: Inserting the buffer material between the handle and the marker allows the room for angular movements. The resiliency of the buffer material repels the lever to return to its initial position. The state of the lever can be estimated by the shift in the center of force.

F) Joystick with a fire button: Radial spatial constraint can be achieved by covering the disk on the bottom of the stick with a soft foam sponge. The detailed schematic is shown in Figure 14. As the user presses the top button, the inner stick pushes the buffer material to transmit more force for triggering the button. For a reliable button triggering, we can utilize the center hole to create a further contact point in the center.

Example: Hot-Swappable Game Controller

When playing video games, we usually play with the same controller regardless of the genre of the game, which hinders immersive playing. We demonstrate the feasibility of ForceStamps to create an *adaptive* physical controller with an example scenario illustrated in Figure 15. In the beginning, a player plays a third person shooter with a directional pad and a joystick (Figure 15A). However, when trying to play another game (*Tanks!*) with the same controller, they feel that the controller degrades the immersive experience. After swapping the layout of the controller with another physical controls, the player may experience a more satisfying gaming experience.

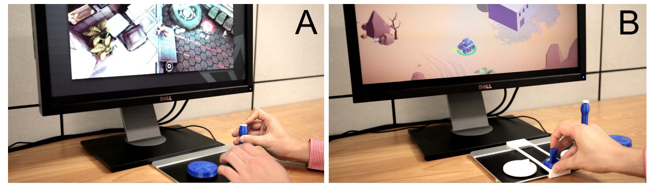

Figure 15: Example: Hot-Swappable Game Controller. A) Playing *Angry Bots* with a directional pad and a joystick, B) playing *Tanks!* with two slider × buttons and a repelling lever.

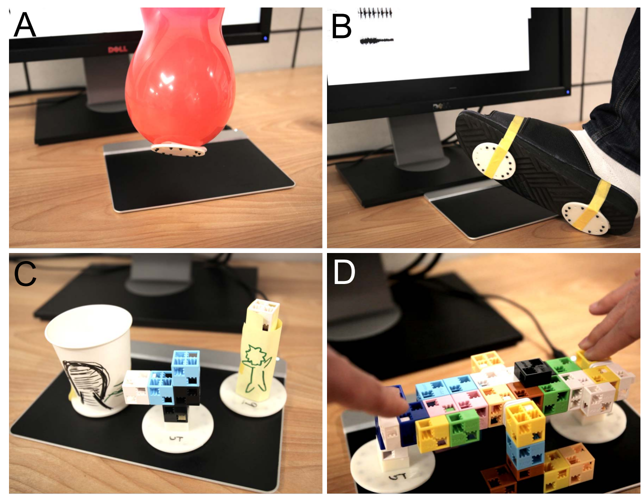

Figure 16: A) Balloon for drum kick control, B) Foot DJ controller, C) Dancing figurines, and D) Cooperative seesaw-like instrument.

Workshop Study: Designing Electronic Musical Instruments

We wanted to understand how competent makers use ForceStamps as a prototyping kit to derive custom physical interfaces. Thus, we conducted a two-day workshop study and recruited skilled eight university students and staff who both have substantial skills in programming and playing musical instruments. Participants were divided into 4 groups of 2 and were instructed to make electronic musical instruments in a total of 8 hours (4 hours per day). The workshop program was roughly divided into four stages: Introduction to ForceStamps and the characteristics of electronic musical instruments (1 hour), ideation and concept design (2 hours), prototyping (4 hours), performance (1 hour). To assist prototyping, we prepared a wide range of materials, such as foam sponge, cotton, building blocks (*ArTec* blocks), paper cups, balloons, straws, cardboard, 13 ForceStamp markers, and the *Sensel Morph* touchpads for each group. For the sound processing platform, we used *Pure Data* and provided some example patches. We also distributed a graphical user interface (Figure 12) for participants to monitor marker attributes and scale the obtained values which are sent to *Pure Data* via *OSC*.

At the final performance session, we observed a diverse range of musical instrument with different attributes of playability. Interestingly, although we did not give specific instructions on inserting buffer materials to manipulate the haptic feedback, two groups made prototypes with various buffer materials to enhance the playability. We introduce several functional musical instrument prototypes from each group developed during the workshop (Figure 16).

A) Balloon for drum kick control (G1): G1 attached a balloon on the marker to achieve intense resilient feedback. They insisted that the feedback from the balloon helps to play rhythm in a consistent time interval while providing pleasing playability. They set a force threshold to trigger the kick while mapping the vertical position of the marker to control the velocity.

B) Foot DJ controller (G2): G2 created a foot DJ controller by attaching two different markers to the front and the rear position of a slipper. They used the presence of markers and the vertical position of the touchpad to play different samples. Foam sponges are attached between the marker and the slipper to make it easier to control the force applied to the markers.

C) Dancing figurines (G3): G3 attached paper cups on the markers and filled them with marbles for weight so that the objects are consistently recognized on the surface. They drew pictures of a human and a locomotive on the cups and treated them as figurines. A player can place multiple figurines to create a scene, and the music changes according to the scene. G3 also tried to map the rotation of the marker to alter the play speed of the music samples.

D) Cooperative seesaw-like instrument (G4): G4 concentrated on creating an instrument which should be played cooperatively. They assembled a seesaw-structure with the building blocks and attached markers on the bottom of the seats. When a player presses a seat, user-defined audio sample is triggered by the applied force, and the user can also add delay effects to the sound by tilting the seat.

5 LIMITATIONS AND FUTURE WORK

Size Constraints

The physical size of the marker restricts designers to design physical controls with much smaller dimensions (e.g., keyboards). In the current design, the minimum size of the marker is determined by the grid resolution of the touch surface. Increasing the sensor resolution is the most straightforward way, but those devices might not be available in the market.

ID Recognition at the Time of Contact

A few participants at the workshop tried to hit the touchpad with markers to play different sounds, but the system recognized a different ID to the marker which led to an error. To acquire the correct ID, it requires that all pins to make contact with the touch surface. We might be able to solve this *occlusion* problem by adopting error correcting codes, but the performance and number of IDs will be limited in the above scenario since such codes have upper limits for error codes. We anticipate that this problem could be solved by using other hardware which can perform pre-touch detection [11].

Design Support

In this paper, we demonstrated several physical controls which can be accomplished by utilizing the attributes of ForceStamp. However, designing such sophisticated geometries from scratch would be difficult for novice users. We plan to generalize the design process by investigating the design space available with ForceStamps. By gathering a variety of material properties, we expect to develop a user-friendly interactive design application.

6 CONCLUSION

In this paper, we proposed ForceStamps, fiducial markers for supporting rapid prototyping of force-sensitive physical controls on pressure-sensitive touch surfaces. We explored various marker designs regarding the ID uniqueness and the structural stability. As well as exploring several design parameters such as geometries and materials, we evaluated the performance of the markers through a series of technical evaluations. We also showcased a wide range of physical controls could be prototyped by utilizing the characteristics of the buffer materials and the spatial constraints. We further demonstrated through a game controller example scenario that a user can rapidly adapt the controller layout to enhance the gameplay experience. In a workshop study, we observed that ForceStamps allowed participants to create novel musical instruments with diverse interactions. Finally, we hope designers and makers leverage ForceStamps to prototype inventive physical interfaces preferably.

7 ACKNOWLEDGMENTS

We thank all workshop participants for their enormous contributions, and also thank Ari Hautasaari for proofreading the paper. This work was supported by GCL program of The University of Tokyo by MEXT, and JSPS KAKENHI Grant Number JP19J14350.

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