FS-Pad: Video Game Interactions Using Force Feedback Gamepad

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ABSTRACT
Force feedback has not been fully explored in modern gaming environments where a gamepad is the main interface. We developed various game interaction scenarios where force feedback through the thumbstick of the gamepad can be effective, and categorized them into five themes. We built a haptic device and control system that can support all presented interactions. The resulting device, FS-Pad, has sufficient fidelity to be used as a haptic game interaction design tool. To verify the presented interactions and effectiveness of the FS-Pad, we conducted a user study with game players, developers, and designers. The subjects used an FS-Pad while playing a demo game and were then interviewed. Their feedback revealed the actual needs for the presented interactions as well as insight into the potential design of game interactions when applying FS-Pad.

Author Keywords
Game interaction; Force feedback; Haptic feedback; Gamepad; Video game; Thumbstick.

CCS Concepts
•**Human-centered computing** → **Haptic devices;** User studies; Pointing devices; •**Hardware** → **Haptic devices;**

INTRODUCTION
Among the 65% of American adults who play video games, 49% use a dedicated game console [4], which is a considerable number. In video game systems, multi-modality is an important property that can allow users to focus on the game [54] and can improve player satisfaction [36]. However, haptic modality in video game systems is relatively under-utilized compared to visual and auditory modalities. The haptic technology found in current video game consoles such as a Microsoft Xbox, Sony PlayStation, or Nintendo Switch is merely simple tactile feedback using vibration motors. However, in studies on haptic-HCI, various technologies using force feedback (FFB) that appear to suit the game interactions have been studied for decades. These techniques include rendering a

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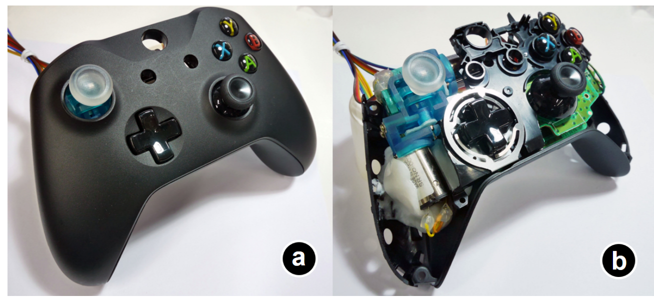


Figure 1. (a) FS-Pad: A gamepad with FFB enabling various game interactions. (b) An FFB thumbstick module is built into the gamepad housing.

physical spring or damper model [21], collision representation [49, 60, 46], or motion guidance [13]. Although haptic technology has a significant potential to enrich the game interaction [9], there seems to be a gap between the abundance of FFB research and the application of real video game systems.

Major video game systems adopt a gamepad as their primary controller, which is held by the hands and controlled with the fingers. To study the effects of FFB interactions in a video gaming environment, an FFB device with a gamepad form factor is essential. Unfortunately, there are no such devices for game researchers and practitioners. Existing haptic gaming devices such as FFB joysticks or FFB racing wheels are inappropriate owing to the differences in the form factor and the limited intermediate haptic control system. As a last resort, game researchers are forced to build their own FFB gamepads. Prototyping a high-fidelity haptic device for FFB interaction requires considerable effort, however. If a novel and easy-to-use FFB gamepad prototype could be made available, studies on new types of game interactions could be expedited, and eventually new FFB interactions would be achievable in real game systems. Therefore, we implemented the FS-Pad (Force Stick Pad), a gamepad that provides FFB on its left thumbstick. We distribute 3D printable models of FS-Pad and its haptic control software to the public[1] in the hope that the device can vitalize new research into FFB game interactions.

In this study, we first organized various game interaction scenarios by referencing and filtering the FFB interactions from previous haptic studies. As a result, we categorized the scenarios into five interaction themes: *reconfigurable input*, *control skill guidance*, *invisible interaction*, *avatar state feedback*, and *dynamic event feedback*. The first three themes are considered

[1]https://github.com/KAIST-HCIL/FS-Pad

novel because most of their interaction scenarios are difficult to implement through pre-existing haptic gaming interfaces. *Reconfigurable input* is a theme utilizing a FFB device as various inputs such as a toggle button, slider, or rotary knob by simulating them. The *control skill guidance* theme was inspired by haptic motion guidance research and helps users to learn to control the thumbstick by physically moving their thumbs. *Invisible interaction* is a theme in which users acquire game information through different force and tactile cues with minimum intervention of visual and auditory channels.

Based on the interaction themes, we organized the system requirements for an appropriate FFB gamepad and implemented an FS-Pad device while considering these requirements. Detailed force rendering and a fast response were made possible by employing the small workspace of the gamepad. Using the FS-Pad, we developed a demo game that uses all five interaction themes. We conducted a user study by demonstrating the game and conducting interviews with users of the FFB gamepad, the game practitioners, and players. Qualitative feedback given by the participants shows their reaction to the new type of interactions, insights into a proper design of each interaction theme, and the actual needs of this type of FFB game interface. The main contribution of this work is three-fold.

- A novel haptic game interaction design that is unavailable with existing haptic gaming interfaces
- Implementation and distribution of FS-Pad
- Findings from interviews with FS-Pad users

RELATED WORK

In this section, we first introduce haptic gaming interfaces and haptic game interactions, referencing commercial gaming products and previous studies. We then review FFB interaction studies that form a foundation of the interaction themes proposed in this study.

Haptic gaming interfaces and interactions

Vibrations, which are frequently employed as tactile stimuli in haptic devices, have been considered an essential part of the gaming experience since they were first introduced in the Nintendo 64 and Sony PlayStation console gamepads in 1997. The basic way to achieve a vibration is to insert two eccentric rotating masses (ERM) into the grip of the gamepad. The Xbox One controller employs two more ERMs in the trigger buttons. Linear resonant actuators (LRA) are also used to deliver high-definition tactile expressions in products such as Nintendo Joy-Con, Nintendo Switch Pro controller, or Steam controller. In addition to vibrations, a skin stretching stimulation has been studied as a tactile medium in a gamepad form factor [19, 17, 18].

FFB devices have long been used as video game peripherals [37]. Representative FFB joystick products have been developed, including Microsoft's Sidewinder Force Feedback series and Logitech's Wingman Force 3D. Video gamers have also typically adopted FFB joysticks in flight simulations. FFB steering wheels such as the Thrustmaster T300 RS are used for racing games. Novint Falcon is a 3-DoF gaming FFB device introduced in 2007. Falcon substitutes the mouse control and generates FFB, such as an arm recoil effect in shooting games. Gravis Xterminator Force gamepad was the first gamepad with an FFB D-pad introduced in 2000. Due to its limited output force, Xterminator Force could not render stiff objects or dynamically affect the user's finger. Recently, Sony introduced the DualSense controller for its upcoming console, with an adjustable tension feature using the adaptive triggers.

Most commercial FFB gaming devices are controlled by an API supported by the operating system. The Windows XInput (previously DirectInput)[2], Mac OS ForceFeedback[3], and Linux Forcefeedback[4] APIs all share an identical control mechanism. The force rendering methods used in these APIs are categorized into two types. One method is a command to output a force with a pre-defined waveform and duration. The other control method employs internal physical models that represent friction, a damper, inertia, or a spring to render the FFB. Because the number of models is limited, other static structures cannot be rendered.

Some researchers have also built 2-DoF FFB joysticks for gaming purposes [38, 41, 5] but with a focus on the mechanical completeness rather than the interaction. In addition, other researchers have employed commercial FFB devices to deliver a recoil effect from a magic skills [2], the elastic force of a slingshot [12], the impact of a table tennis racket [33], or the feeling of textures and shapes for puzzle games [26]. These studies were conducted based on an absolute control scheme using 3-DoF inputs, which is not a general practice used in video games. In addition, devices employed in such studies have been limited by their form factor to better represent a modern gaming environment where the gamepad is the main interface.

In terms of form factor, Foldaway has the most similar properties to those of FS-Pad. Foldaway [32, 47, 48] is a 3-DoF portable FFB origami robot controlled by the fingers. Although its form factor can imitate a thumbstick, studies have only explored its use in virtual reality, education, and drone control.

Base force feedback interactions

In this subsection, we review studies forming the base of game interaction themes, which we will elaborate on in the following section. We focused specifically on the first three themes: *reconfigurable input*, *control skill guidance*, and *invisible interaction*, because the latter themes of *avatar status* and *dynamic event feedback* represent interactions that are already employed in video games.

Reconfigurable input

The main concept of the *reconfigurable input* theme is simulating an FFB thumbstick for various types of input devices. To select candidate input devices for simulation, we referred to studies that tried to simulate GUI inputs or real machines. Kelley and Salcudean [24] employed a haptic mouse to simulate

[2] https://docs.microsoft.com/en-us/previous-versions/windows/desktop/ee417563(v=vs.85)

[3] https://developer.apple.com/documentation/forcefeedback?language=objc

[4] https://www.kernel.org/doc/html/latest/input/ff.html

GUI widgets, such as a linear slider or a push button. With a 2-DoF FFB interface called Moose, O'Modhrain and Gillespie [39] planned to mechanically present buttons, sliders, and pull-down menus inside the digital sound studio application for visually impaired users. In addition, Smyth et al. [52] presented a unique haptic widget for text editing on a bi-manual interaction environment where the users control the Phantom FFB device with their left hand and the mouse with their right hand. In addition, Angerilli et al. [3], Frisoli et al. [15], and Gil et al. [15] independently implemented and verified a 2-DoF FFB joystick to simulate a manual gearshift of an automobile. Moreover, Doerrer and Werthschuetzky [11] built a 1-DoF FFB device to simulate a physical push button. Recently, Liao et al. [28] expanded on this idea and implemented a haptic interface and a recording system for simulating the pushing of a button.

All FFB devices partially share a common property with a tangible UI and a shape-changing UI. That is, they support various inputs and outputs with a single interface. For instance, Shahrokni et al. [51] used an FFB slider as a slingshot-like input for a catapult game or a haptic display that represents the amplitude of a sound wave. KnobSlider [25] is a shape-changing device that directly switches between a knob and a slider. The inFORM [14] project presented applications implementing a button, 1D touch track, 2D touch surface, and handle with a shape display. PinPad [23] suggested a scenario of dynamically generating GUI widgets such as a slider or a checkbox with a touch-sensitive pin array.

Control skill guidance

In the *control skill guidance* theme, an FFB thumbstick moves by itself while the user's thumb is placed on it, guiding proper movements for game control. Such motion guidance studies have been explored in the haptic-HCI field. Yokokohji et al. [58] presented the concept of recording expert movements and playing them to the trainees. Gillespie et al. [16] organized the metaphors of a teacher physically guiding the students and tested them with a crane controlling task. Feygin et al. [13] used a Phantom haptic device to verify how combinations of visual and haptic stimuli and training and recall methods affect the motor training process. It was determined that haptic training has a dominant effect on the temporal accuracy. Morris et al. [34] showed the magnitude of the force, the timing of which can also be trained using FFB when drawing a spatio-temporal trajectory. A motion guidance technique has also been applied to rehabilitation [27], surgery training [7, 57], and calligraphy training [22, 53, 55]. The GestureOutput [45] study proposed a touch gesture training interface using FFB. The Training section in Maclean's review paper [29] has more information on this.

Invisible interaction

It is natural to identify an object or gather information from circumstances using tactile cues and proprioception. The *invisible interaction* theme is closely related to this natural user behavior because its main concept is delivering information of the game world through systemically designed haptic cues. Conveying formatted information using an FFB device was initially studied to help visually impaired users. Yu et al. [59] represented a graph with a Phantom device, and Moustakas et al. [35] proposed a haptic rendering method for representing 3D and 2D maps. Pannels and Roberts [40] thoroughly reviewed this topic and categorized the studies following the data type represented, i.e., chart, map, sign, network, diagram, image, and table. DualPanto [50] is an interface allowing visually impaired users to explore inside a virtual environment. The authors employed two pantograph devices to represent situations in a digital game using the direction and relative position of two end-effectors and required the users to handle the end-effector to control the game avatar.

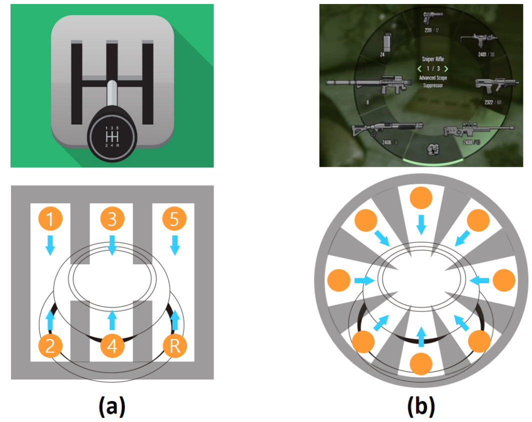


Figure 2. Examples of reconfigurable inputs. A gray area indicates a virtual wall, blue arrows represent a passive resistance in that area, and orange dots indicate the game function activation. (a) An auto-vehicle gearshift can be abstracted on FS-Pad. (b) A marking menu interaction could be guided with haptic "track."

INTERACTION THEMES

We composed possible game interaction scenarios using an FFB gamepad while referring to previous FFB interaction studies. We produced various scenarios through brainstorming sessions, in-lab workshops, and an in-depth interview with a video gamer. We then analyzed the scenarios and categorized them into five themes. Each theme is not completely exclusive of the others, and thus more than one can be used to form a single game element.

Reconfigurable input

There has long been a need to use dedicated input devices tailored to specific game situations. This desire has led the gamers to use various controller shapes such as a racing wheel, flight stick, or even guitar-shaped controller. The VoodooIO gaming kit [56] and HOT SWAP [20] project were attempts at achieving a configurable game controller, which made the users switch various control gadgets into a controller-shaped platform for game-specific inputs. An FFB device affords a proper physical controller following the specific game situation on the fly by simulating different input devices. Because the switching time between inputs on the FFB device is instantaneous, the user can seamlessly continue the gaming experience.

A number of input devices can be implemented using an FFB gamepad. These include a toggle switch, slider, rotary knob, or even automobile gearshift (Fig. 2 (a)). For example, assume that the user needs to turn the volume down in the settings menu. With a conventional gamepad, the user selects the volume item in the menu and pushes a button several times or holds it to turn the volume down. With an FFB gamepad, when the user selects the volume item, the thumbstick moves to the current position of the GUI volume slider automatically, and its movement is limited to upward and downward motions to simulate a physical slider. The user pulls the stick down to a desired level.

Another example is a marking menu (Fig. 2 (b)). A marking menu is a frequently used UI component in games when the user needs to select an item rapidly from multiple choices. The conventional marking menu selection sequence from a gamepad is as follows. First, the user presses the mode-switching button. The marking menu GUI then appears on the display. The user tips the thumbstick toward the direction of the target item to be select. When using this type of control, the possibility of mis-selecting the item increases proportionally to the number of items. The user is likely to tip the stick in the wrong direction and be unable to recover once the stick as already passed the confirmation angle. This problem can be handled through FFB augmentation. We can provide a physical track toward the direction of each item preventing the user from mistakenly tilting the stick in the wrong direction. In addition, we can add a slight repulsive force right before the confirmation angle that the user can perceive, allowing the user to proceed in selecting the item.

The last example scenario is thumbstick customization. Gamers customize their gamepads to enhance the controls or meet their preferences. They may open the gamepad and change the spring of the thumbstick to adjust the stiffness. Similarly, arcade gamers might modify the restrictor gate, which is a physical mask that blocks the joystick to determine the shape of the movable range. For the FFB gamepad, these customizations can all be done through software, and the settings can be saved and used for each game independently.

Control skill guidance

Because the user's thumbstick control motion is also a body movement, the user can train using the haptic motion guidance, i.e., by feeling the movement of the stick actuating by itself while placing a thumb on it. This theme can be applied to tutorials in any game. For example, the thumbstick can tilt forward by itself, and the avatar shown in the visual display can move forward to guide the user in how to move the avatar. Furthermore, the theme can be applied in games where timely control is essential. The skill commands in fighting and sports games are determined by a sequential thumbstick input and button combination. The user practices these commands in the training mode. When the user selects a specific skill command, a video of the avatar's action appears with control icons. The training can be strengthened when the FFB thumbstick moves at the exact time matching the video (Fig. 3).

Indirect training can also be included in this theme. Gamers watch gameplay videos of professional gamers or game streamers to improve their skills and for entertainment purpose. However, it is difficult to guess the exact direction and angle of an analog stick by simply watching a video. The *control skill guidance* theme can augment this game replay experience by recording the thumbstick's movement during the gameplay.

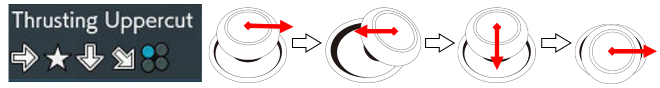


Figure 3. Control skill guidance example. FS-Pad can directly move the thumb of the user to teach the skill commands. Red arrows indicate active FFB by a thumbstick.

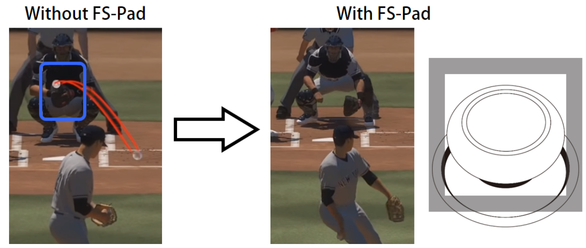


Figure 4. Invisible interaction example. FS-Pad helps to aim without seeing by indicating a strike zone with a virtual wall (a rectangular gray area).

Invisible interaction

A haptic display is effective when it is difficult to use a visual or auditory channel as the main output. For a specific game interaction, the game designer can intentionally limit the other channels and make the act of venturing into a haptic virtual space itself a challenge. For example, the FFB gamepad can render tension to a fishing rod in a fishing game. The force on the thumbstick can increase as the fish violently swims. Because the fishing line may snap when the tension exceeds its limit, the player should try to control the stick toward the direction where the resistance weakens. Another example is an unlocking of a numbered lock puzzle. The user may have to rotate the stick in a circular path to change the number in a slot and match a password by feeling the different tactile cue when the number snaps into the slot. Finally, finding an exit in a maze could turn into a tactile puzzle game. The user could feel a stiff virtual wall and head toward the goal.

For another *invisible interaction* scenario, consider a local multi-player [8] environment where multiple users play using a single game console. Under such a setting, the players should share the visual display and sound. However, they may need to obtain game information individually or hide information from other players according to the situation in the games. The FFB gamepad can serve as a private communication channel. For a sample scenario, consider a baseball game (Fig. 4). The pitcher can control the thumbstick to adjust the trajectory of the ball toward a square-shaped strike zone. However, the batter can see the direction of the ball and take advantage of this information, making the game unfair. Instead, we can apply a FFB interaction to handle such a case. We can eliminate the visual effect of the trajectory and instead render a square-shaped border on the FFB thumbstick's workspace to indicate the strike zone. The pitcher can then determine the position based on the tactile cues.

Avatar state feedback

One of the major roles of a gamepad is to control the avatar or movement of an object. Depending on the situation in the game, the avatar can have various kinematic states. The avatar could slow down if it falls into a swamp or when pushing a box. Conversely, it may move faster when wearing magic boots. Game designers will be able to improve the immersion of the user and control the challenge level of the game by expressing the kinematic state on the FFB gamepad. We can intensify the damping coefficient of the thumbstick to represent the difficulty of movement felt by the avatar. This physical representation would hinder the user's control, therefore inducing the user to avoid such a disadvantage during the game. As another example, we can apply an *avatar state feedback* theme into a sports game, such as the individual stamina or condition of the characters. If the character becomes exhausted or injured, its speed and ball control could decrease. Representing such a state by increasing the stiffness of the thumbstick could be a direct representation of the character's physical condition.

Dynamic event feedback

Game effects are visual, auditory, or tactile stimuli used to emphasize the aesthetics, reality or surrealism, narrative, and other factors, of a digital game. Conventionally, stimuli applied through tactile or haptic channels have been used for intense expressions such as collisions, shocks, explosions, and the recoil of an arm based on the ability to transmit a physical force. Describing such sudden and impulsive game effects through force is the main concept of a *dynamic event feedback* theme. Most game interactions used with a commercial FFB joystick or steering wheel therefore belong to this theme, e.g., an impact when a plane becomes damaged by bullets in a flight shooting game or a sudden rotation of the steering wheel when a car collides with another vehicle. However, we can apply this theme in other game genres that are controlled using gamepads. The recoil of an arm in a first-person-shooter (FPS) game or damage when attacked from a monster in an adventure game could be represented by abruptly moving the stick toward the direction of impact. These effects may surprise the user in a positive sense and improve the feeling of immersion.

SYSTEM IMPLEMENTATION

To explore the FFB interactions in a modern video gaming environment, we built FS-Pad, a gamepad that employs its thumbstick as an FFB end-effector.

Requirement

We needed a performance goal to build the FFB gamepad. From an engineering perspective, it is necessary for the device to satisfy certain mechanical specifications such that the user perceives an artificially generated haptic stimulus in a natural way. Additionally, the device should support all scenarios suggested from the interaction themes. Therefore, we set up the requirements such as the mechanical performance and functions supported for applications.

Mechanical performance

To generate a haptic stimulus that feels natural, we need to design the device to support a fine resolution that exceeds the perceptibility of a human user. In Table 1, we listed up engineering factors that determine the naturalness of the device and set up the minimum value for each factor when considering the characteristic of the FFB gamepad.

Property	Set up level	Measured value
Maximum stiffness	$> 20\,\mathrm{N/cm}$	**X, Y**: $57\,\mathrm{N/cm}$
Maximum force	$> 8\,\mathrm{N}$	**X**: 3.21 N, **Y**: 2.94 N
Update frequency	$> 1\,\mathrm{kHz}$	44 kHz
Back-drive friction	$< 0.1\,\mathrm{N}$	**X**: 0.02 N, **Y**: 0.09 N

Table 1. Mechanical performance requirements and specification of the FS-Pad. X and Y indicates each axis of the FS-Pad

The maximum stiffness is a measure of the hardness of a virtual solid object. According to Massie and Salisbury [30], user reported feeling an object as sufficiently hard at a minimum stiffness of $20\,\mathrm{N/cm}$. For the maximum force property, it would be ideal if the output of the device can cover the force spectrum of the thumb. To the best of our knowledge, there are no existing studies on measuring the tangential force generated by a thumb. We conducted a short in-lab study to measure this force. Three participants (three males) were required to hold a fixed Xbox One controller and push the left thumbstick to the left as hard as possible. The average peak force generated was approximately 8 N. The update frequency determines the speed of the haptic rendering cycle. It is suggested to be maintained at above 1 kHz to exceed the haptic perception range of a human user [21]. The back-drive friction, inertia, and unbalanced weight all affect the quality of free movements of the end-effector [30]. We considered the back-drive friction to match the ordinary characteristics of the thumbstick. The inertia and unbalanced weight are neglected because they are almost unable to be measured on the small form factor of the thumbstick.

Supported functions

We need three common application functions to implement all the scenarios proposed from the interaction themes. Even scenarios from different themes can share an identical functional requirement. For example, generating virtual walls upward and downward to implement a slider widget in the *reconfigurable input* theme is similar to creating virtual walls to implement a maze puzzle in the *invisible interaction* theme. We elaborate on each functional requirement below.

Low latency static structure rendering: FS-Pad should be able to render various haptic structures, including a detailed expression and spatially discontinuous layout. For example, it should render a structure that blocks the stick's movement by generating a star-shaped virtual wall. Various widgets suggested in the *reconfigurable input*, or *invisible interaction* theme will be implemented using this technique. To eliminate an unnatural feeling from the rendered structure, the haptic effect based on the stick position should be immediately reflected to the actuators, sustaining an update rate of above 1 kHz.

Low latency position control: Every scenario in the *control skill guidance* theme is based on the position control function, which allows FS-Pad to move the thumbstick to the desired position at the desired time. This function is also required in the *reconfigurable input* or *invisible interaction* theme to move the initial position of the stick when switching into different input modes. Moreover, FS-Pad should be able to apply a sequence of stick movements to implement complicated mo-

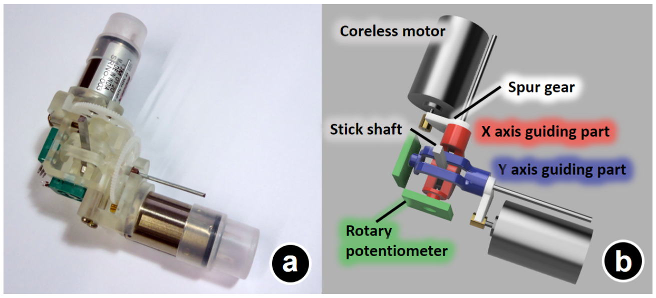


Figure 5. (a) The FS module. (b) A rendered figure showing the FS-module components. The case is excluded from the image for better visualization.

tions and control the movement speed. Pre-existing haptic gaming devices cannot sustain a consistent movement of the end-effector owing to the latency between the PC and the device. The FS-Pad should support a low latency to allow the movements to be accurately controlled.

Changeable spring model: FS-Pad should be able to render a spring model and emulate an ordinary gamepad thumbstick for general use. In addition, FS-Pad must control the strength of the spring when implementing chages in stiffness according to the kinematic state of the avatar for the *avatar state feedback* theme or thumbstick customization for the *reconfigurable input* theme.

Hardware

We call the FFB thumbstick component the FS module, which is shown in Fig. 5. The stick shaft is connected to the guiding parts that manage the rotation of each axis and form a 2-axis gimbal structure. One end of the guiding part is linked to the rotary potentiometers, which are detached from a thumbstick module (ALPS RKJXK122400Y), and the other end is glued to the spur gears. The potentiometers measure the tilt angles of the stick about the two axes. The spur gears are coupled to smaller spur gears on the motor. The coupling amplifies the output of the motors by a ratio of 70:11. The stick shaft was made by laser-cutting the stainless steel, and the guiding parts and case of the module were 3D printed (Formlabs Tough Resin). To satisfy the mechanical performance requirement, we selected coreless motors (16DCT Athlonix 219E), which have no cogging and possess small inertia owing to their light mass. The stick's movable range is from $-18°$ to $18°$ for each axis, and the distance from the rotation center to the end-effector is 23.4 mm. We referenced existing gamepads to determine the physical dimensions [6].

To form an FS-pad, we packaged the FS module using the housing of an Xbox One controller. We cut out the shoulder button, trigger button, and half of the PCB to make space and attached the FS module using Shapelock thermoplastic. We kept the ABXY buttons on the pad and connected the wires on the PCB for use as inputs.

We used a Teensy 3.6 processor to manage the haptic control system. The Teensy device obtains the thumbstick position from the potentiometers and the on/off states of the ABXY buttons. It also outputs PWM signals to control the motor drivers (DRV8801). The signals are eventually amplified at

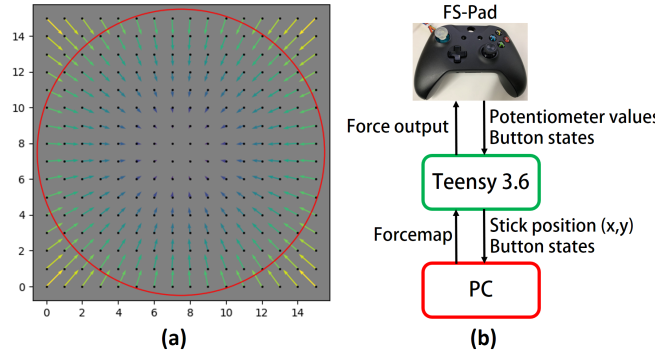


Figure 6. (a) A visualization of forcemap used by the spring model. The red circle indicates the movable range. (b) A system diagram showing the data flow.

up to 9V to control the actuators. The Teensy device communicates with the PC to send the position of the stick and the pressed state of the buttons and receive haptic control commands (Fig. 6 (b)).

Haptic control system

The Teensy device manages the haptic rendering by continuously adjusting the output of each motor according to the position of stick. Haptic rendering on the intermediate processor is an effective technique [1, 10] because it could avoid slow data transmission between the PC and the actuator and alleviate the computing load of the PC. It is also applied to commercial FFB joysticks and steering wheels. These products employ internal physical models but have limited rendering options, therefore unable to render detailed static structures.

In our control system, we use a pixel-based model [31] called a forcemap to enable detailed rendering. A forcemap is a table that holds the force vector values for rendering of each discretized position within the workspace. A total of 16×16 grid points are used for the forcemap. Note that the number of data points can be changed. For every rendered loop, the system calculates the output force by linear interpolating the force vectors of the four nearest points from the current position of the stick and controls the motors. Fig. 6 (a) shows an exemplar forcemap of a spring model. At any position, the interpolated force vector congregates at the center, and its magnitude increases linearly as the position moves away from this position. Various spring models can be implemented by controlling the magnitude of the force vectors.

A forcemap can be easily handled by an intermediate processor owing to its small data size. As a result, FS-Pad can rely on Teensy's fast update rate to render detailed static structures. The control loop is repeated at a high speed of 44 kHz. In this way, low latency static structure rendering can be achieved. In addition, position control can be implemented using a forcemap. We apply a forcemap with force vectors that congregate to a specific position. When this forcemap is uploaded, the thumbstick moves to the focus point of the force vectors. By changing the focus point and repeating the uploading process, we can smoothly control the position of the stick. The round-trip communication delay between the PC and the Teensy device is as short as 5 ms, and thus a consistent position control is possible.

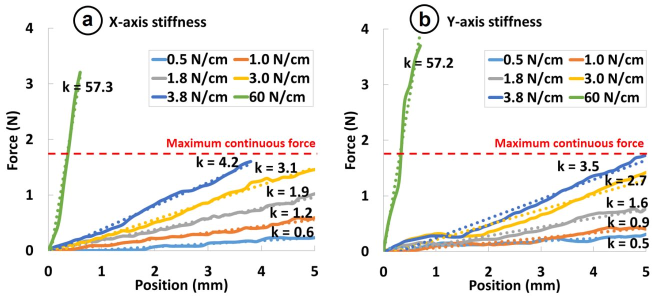
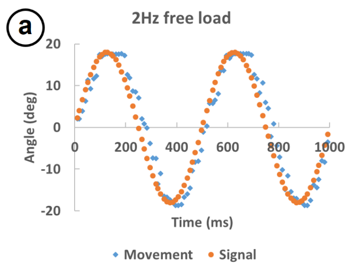


Figure 7. Results of various stiffness rendering on (a) X-axis and (b) Y-axis. Dotted lines indicate linearly fitted lines.



(b)

	Latency (ms)		RMSE (Deg)	
	Free	Load	Free	Load
1 Hz	16.7	16.7	1.41	1.36
2 Hz	16.7	16.7	1.25	1.82
4 Hz	16.7	16.7	1.99	2.81
8 Hz	16.7	16.7	2.84	5.26
16 Hz	16.7	33.3	4.46	16.11

Figure 8. Results of position control evaluation. (a) 2Hz free-loaded condition. The waveforms for 2Hz loaded condition is similar. (b) Table of latency and root mean square error for each condition.

Specifications

The right column of Table 1 shows the measurement results of FS-Pad for the mechanical performance requirements. Excluding the maximum force property, all other properties are satisfied. A set up level of 8 N was determined based on the temporal peak force of the human thumb, although it is difficult to maintain this maximum force for a long time under real gaming situations. Massie and Salisbury [30] reported that the time-averaged force exerted during normal operation with the hand is only on the order of 1 N. Therefore, we concluded that the maximum power of about 3 N would be sufficient for the research's purpose.

We measured the force output and position control ability of FS-Pad to evaluate the mechanical completeness and prove that the requirements are satisfied. First, for a force output evaluation, we tested six stiffness conditions (0.5, 1.0, 1.8, 3.0, 3.8 and 60) N/cm. The former five conditions were rendered using a spring model forcemap, and the 60 N/cm condition was rendered using a virtual wall forcemap. We measured the output with a force gauge (IMADA DS2-20N) connected to the end-effector with a string for every 0.1 mm step. Measurements were conducted on each axis. Fig. 7 shows the results. We used linear regression for the post-analysis. The R^2 value of the X-axis data was 0.98 (SD: 0.02), and that of the Y-axis data was 0.94 (SD: 0.03), indicating that the spring models are sufficiently linear.

To evaluate the quality of position control, we measured the physical movement of the FS-Pad stick and compared it with an input signal. The sinusoidal input signal controls the stick, allowing it to move from side to side with the maximum movement range. The measurement was conducted under five frequencies (1, 2, 4, 8 and 16) Hz conditions and two loads (free-load, load) conditions. For the load condition, a 35 g weight is attached to the end of the stick to emulate the pressure of the thumb. The physical movement of the stick was recorded using an OptiTrack motion tracking system (Flex 13, 120 Hz). Example recording results are shown in Fig. 8 (a). We derived the latency by calculating the cross-correlation between signals while phase-shifting the input signal. The phase-shift maximizing the correlation is considered as the latency. The result is shown in Fig. 8 (b). Because the amplitude of the movement significantly decreased under the 16 Hz conditions, we considered only the latency values from the conditions within 8 Hz. Therefore, the average latency is approximately 16.7 ms. This latency is longer than the sum of the round-trip communication delay and the period of the control loop. The motor is delayed in moving its load, owing to the inductance and inertia. In addition, the measured latency can be longer than the actual latency because the temporal resolution of OptiTrack was 8.3 ms (1/120 Hz). This is also why most of the latency values are the same in Fig. 8. Nonetheless, the measured latency of FS-Pad matches that of the visual display, and the game players will perceive that the visual and haptic output are given at almost the same time. This satisfies the required low latency position control. In addition, the root mean square error (RMSE) of the input signal and the output motion for each condition are shown in Fig. 8 (b). Except for the 1 Hz condition, the RMSE was higher when the load was attached. However, the actual distance error was not severe. Conditions within 8 Hz had an error of less than 5.5°, which is approximately 2.2 mm when translated into the movement distance.

USER STUDY

We conducted an interview with game players, developers, and designers to obtain objective feedback of the presented game interaction themes and FS-Pad. Our goal here is to offer detailed participant reactions, comments, and behaviors such that their actual needs and insights regarding the interactions are well described.

Participants: We recruited four game players (P1-4, 1 female, avg. age: 23.0, STD: 3.2) who have experience in console video games and four-game practitioners (P5-8, 4 males, avg. age: 28.5, STD: 7.5). We posted a recruitment notice on an online community and directly contacted the game development company to gather the participants.

Apparatus: The study was conducted in an empty office. We set up a laptop (MacBook Pro, A1706) and the FS-Pad for a game demonstration.

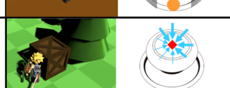
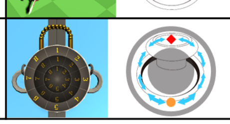
Procedure: First, we described the goal of the study to the participants. We then, guided the participants to play the demo game. We also described how to play the game using FS-Pad verbally and the participants learned the controls through a tutorial. Each participant played the game until the end to experience all game elements. After the game demonstration, we conducted an interview with the participants. We elaborated on each game interaction theme and its following use cases. We asked the participants if they had any ideas for a new FS-Pad interaction, what improvements in the interactions should be made, which aspects improved the game experience, and what differences they noticed between FS-pad and ordinary gamepad experience. The participants were free to make any comments, and we recorded the audio of the responses. After the interview was over, we translated the recorded comments into text for analysis.

Demo game

We built a 3D adventure game using the Unity game engine to support all five game interaction themes using FS-Pad. Note that the design factors using FS-Pad and the game components should be harmonized to elicit a satisfactory gaming experience. Our design goal was to build a game that contains sufficient elements to feel like a full game.

The overall game interactions are summarized in Fig. 9. The participant controls a swordsman avatar by moving the thumbstick and uses two discrete buttons for attack and object interactions. The avatar can apply a normal attack or a skilled attack. A normal attack is immediately triggered when the attack button is pressed and slightly damages the monster. A skilled attack starts by entering a specified command (flicking the stick twice and then pressing the attack button) and incurs significant damage. During the tutorial, the participant's entry (the direction of the stick movement and the buttons pressed) appears through visual icons, and the participant could preview the commands to learn how to make a skilled attack. The *control skill guidance* theme is applied to the preview. When the preview button is clicked, visual icons quickly appear, and the thumbstick flicks by itself to indicate that a skilled attack command has been implemented.

We designed the main map to make the participants encounter the game subtasks sequentially in a controlled order. The first subtask is to battle a monster. The monster attacks the avatar when it gets close. When the avatar is attacked, a short constant FFB is delivered (*dynamic event feedback*) through the FS-Pad.

Game element	Illustration	Description
Tutorial: skill preview		A thumbstick flicks twice automatically.
Monster attack		An impact (2.2N) generated for 0.5 sec to the damaged direction.
Lever widget		The peak resistance at the middle is 2.2N.
Box pushing		Force applies to the opposite of the pushing direction (1.7N).
Lock puzzle		Normal tactile dimple's peak resistance is 0.53N & hint cue is 1.7N.

: Active force feedback   : Passive resistance   : Virtual wall   : Stick initial position   : Function activation

Figure 9. Table showing the FS-Pad interactions used in the demo game.

The avatar of the participants faces a river after the first battle. A lever is placed by the riverbank, which is a switch to create a bridge to help the avatar cross the river. The lever is a part of the *reconfigurable input* theme. When the participant presses the object interaction button, the view switches into a lever control state. The thumbstick moves upward at the same moment to emulate a real lever. The participant should pull down the stick while overcoming the resistance of the lever.

On another river, the participant must push boxes into the water to use them as stepping-stones. The box slides when the avatar moves ahead to it. The box pushing state is an implementation of the *avatar state feedback* theme, and the participant needs to exert significant force to move the box because the stiffness of the stick toward the box direction increases.

At the goal point, the castle door is locked. We employed the lock puzzle scenario introduced in the *invisible interaction* theme. The participant should guess the password using tactile cues and must match three numbers on the lock by rotating three circular layers. When the participant presses the object interaction button, the view zooms into a lock, and a circular forcemap is loaded onto the FS-Pad, which allows the thumbstick to move only in a circular track. In addition, the thumbstick fixes into eight positions, which indicates that a number from 1 to 8 is positioned into the slot. This generates the feeling of tactile detents between numbers, which is felt when rotating a real lock. Although it is easy to turn the lock between non-answer numbers, the resistance increases when turning into or out from the answer numbers. When the participant matches the password, the castle door is unlocked, and the game ends.

User feedback

The participants positively reacted when asked to assess the game interactions and the overall use of FS-Pad.

Novel dimension of experience: P7 emphasized the expandability of the FS-Pad interactions, stating that "usually it is visual or auditory effects that people expect from a game . . . It feels like now there is a third axis when the game's movement and the effects of FS-Pad are harmonized". P8 stated, "I thought gamepads do not really differ by companies these days, and they can't evolve anymore. Today I saw this (FS-Pad) and was amused because I now realized that gamepads can be improved. . . . I'm happy to know that gamepads can evolve further, both as a game player and as a game developer."

Effective game genres: The participants expected that FS-Pad will offer a powerful experience, especially with specific game genres, such as adventure (P1), puzzle (P2, 3, 4, 8), and horror (P7) games. P8 wanted "to make a puzzle game with this type of gamepad . . . because is suitable for games with gimmicks such as escaping a room by moving obstacles".

Different from vibration feedback: Some participants compared the role of FS-Pad FFB and gamepad vibration feedback and stated that the FS-Pad will "show its true ability when both stimuli are employed together" (P7). Whereas P6 stated "I did not think a tactile sensation, I mean a vibration, could transfer much information, but this (FS-Pad) device can be used in various ways," P3 pointed out that the FFB of FS-Pad "affects a narrow area because it stimulates one finger" and advised that some game effects will be appropriate with a vibration feedback "that covers the whole pad."

The participants made detailed comments on the interaction themes after playing the demo game and listening to the concept and scenario of each theme.

Reconfigurable input: The participants liked the interaction scenario examples of the theme and the lever interaction of the demo game. P2 liked the customizable stick because "it will be fair to use identical hardware when running a console game tournament and simply ask the participants to adjust the device to their personal settings." P3 empathized with the marking menu scenario, referring to his personal experience, stating that "There is an arm wheel selection interaction in Grand Theft Auto that should be done with the right thumbstick. I mistakenly select the wrong weapon occasionally since the stick has no physical guides." P6 stated that "Pressing a gamepad's button when I have to press a button inside a game is an immersive experience, and it seems like this interface will offer a greater chance of experiencing this type of immersion." However, some participants felt it was difficult to pull down the lever emulated by the stick when playing the demo game and suggested "reducing the force" (P1). They also felt puzzled when "the stick suddenly got stuck, but no guide was given" (P3), and when "the stick suddenly went upward" (P7). To improve this interaction, they wanted a "tutorial in the form of a video or a flash animation" (P1).

Control skill guidance: Most participants highlighted their needs on the *control skill guidance* theme and its effectiveness. Based on a detailed personal experience, P3 stated that, "When playing a soccer game, skilled moves are difficult to become familiar with. Game descriptions say that some skilled moves need a short stick control and others need longer control. This is always confusing, and it would be good to train for the timing of the moves and become used to the skilled moves". P8 liked the theme because "it is better to feel once than to see a hundred times." By contrast, P5 claimed a need for a quantitative evaluation of the theme by "comparing the physical movements and a graphical representation of gamepad control." In addition, P7 commented that "the moving direction was perceptible, but the distance of the movement was difficult to perceived. ... It is extremely difficult to know how the stick is moving when controlling it at the moment of actuation." This implies that a further evaluation is needed to achieve on a better perception of movement.

Invisible interaction: The participants commented on the uniqueness of the demo game's lock puzzle, stating that it is "impossible to implement without this pad (FS-Pad)" (P1) or that "other consoles do not have such a feature" (P4). All participants except P6 successfully cleared the lock puzzle based on the tactile hints. Regarding the given force, P1 stated that the difference in strength of the hint was "appropriate because a smaller difference will make it hard to finish the task," whereas P3 wanted "smoother feelings on non-answer slots because the tactile feelings were fairly similar."

Avatar state feedback: For the box pushing interaction in the demo game, the participants felt it to be "very natural and reasonable" (P4) and it "was easy to accept and was fun" (P7). Other participants stated that it was "the exact interaction I imagined when I heard the description (of FS-Pad)" (P6), or is the scenario that "comes to mind" when imagining such a device (P5). Meanwhile, some participants did not feel the FFB well and asked: "Was there any resistance?" (P2) or "Did it become stiffer when pushing the box?" (P3).

Dynamic event feedback: In the demo game, this theme was applied to the situation in which the monster attacks the avatar. The participants felt that interaction was "uncomfortable" (P1), "embarrassing" (P8), or "excessive" (P6, P8), and were concerned that it could be an "unpleasant experience" (P6, P7). They described the basis of these negative emotions as "being startled from a sudden output" (P7), the avatar "not reacting to me but moving by itself" (P6), "not liking the controller going outside gamer's intention" (P1)", and "disturbs the next move" (P8). P1 asserted that the "on/off option should be provided."

The participants actively suggested new interaction scenarios. For the *control skill guidance* theme, P2 suggested an "assist mode." This mode is for "users who want to clear the game in easy mode" and includes use cases such as "actively correcting the control by moving the stick to the desired position to achieve the optimal path in racing games" and "automatic aiming in FPS games." P6 and P8 imagined a "mining scenario," which applies an *invisible interaction*. Under this scenario, the user can find and choose valuable mineral resources when using a pickax because "the stick delivers a repulsive force when mining for diamonds and moves freely when simply digging in the ground." An *avatar state feedback* interaction such as "making the stick control tougher when a vehicle needs repair" (P8) for racing games and a *dynamic event feedback* such as a "stuck control effect when an avatar is stunned" (P7) were also suggested.

Design considerations for FFB game interactions

Analyzing the feedback from the participants, we found detailed requirements of and positive responses to the FS-Pad and the interaction themes. In addition, we found that some interactions can be ineffective or even harm the game experience when improperly designed. We next discuss properties that should be carefully handled based on these insights.

Characteristics of active feedback: The participants easily accepted passive feedback, initiated by their active control (e.g., increased stiffness when pushing a box), but were embarrassed when the stick itself actively actuated when they gave no specific stick control. In the demo game, this active feedback case includes a skilled attack preview, a monster attack, and the stick moving upward when switching into the lever state. P5 commented on the active feedback, stating that "Because a controller is a controller, I think I have control over it. When it (the FS-Pad stick) moves by itself, it could be recognized as malfunctioning or not being controllable by the users." The participants thought the users would easily accept the feedback of a skill preview and lever emulation if visual guidance is provided. The monster attack case received the most negative reviews from the study, one of the reasons for which was that the stimuli made the stick to slip out of the user's thumb. This made some participants perceive this interaction as a control-disturbing element rather than an expression of a collision. It would be better to not use this feedback or at least reduce the strength of the force. However, we do not intend to omit active feedback from the game design unconditionally. Such feedback is still a powerful interaction depending on how the users can adapt to it and when used with the appropriate context of the game. This is revealed in the participants' suggestions, such as representing the forced movements of the avatar when "possessed by a spirit" (P6), "on a conveyor belt" (P6), or "employing the stick's autonomous movement as a source of fear when designing a horror game" (P7).

Insensitiveness at physical limit: Some participants did not sense an increased stiffness when pushing a box. When we had the participants replay the box pushing again, they perceived the change in resistance immediately. Through several observations, we found that when the participants tilted the stick all the way to the physical edge, they did not recognize the increased stiffness well. This is because the force that the participant senses is a sum of the output force of FS-Pad and the reaction force of the physical edge, i.e., if the participant applies excessive force to the stick, the participant will not feel the difference in the force because the reaction force from the edge will decrease as the same amount of increase from the output of the FS-Pad.

Performance impeding interactions: Game players are sensitive to game elements that disrupt their performance. The participants advised the players will perceive an unfairness if only one player is disturbed by an interface when playing an online multiplayer game and would try to turn off the option. By contrast, P8 suggested applying performance impeding interactions into a local multiplayer environment. He stated that, "if the computer distracts me, it makes me get mad at the game itself, but if that agent is my friend, it will arouse a sense of rivalry and make the game fun." It is known that a player's gaming experience differs based on the game environment, i.e., single/multiplayer or type of co-player (computer, stranger, or friend) [43, 42]. Game designers may have to consider the effect of the environment when designing FFB interaction.

Importance of proper force levels: While most participants agreed that the tactile force in the lever interaction should be decreased, their opinions were contradictory for the level of tactile hints for the lock puzzle. This implies that although there is a range of stimuli that all users feel as unpleasant, they also have different preferences within the proper range. Apart from such preferences, the ability of humans to perceive the strength of the force should also be considered in the game design. For example, the game designer can increase the difficulty of the task by offering insignificant tactile hints or reliably deliver information to the user with strong force stimuli.

FUTURE WORK AND LIMITATIONS

A gamepad is a bi-manually controlled device. Some game control methods guide the players to use two thumbsticks at the same time. It is possible to employ two FS-modules in one FS-Pad but were not tested in the current study. Although it is theoretically possible to apply independent FFB interactions on each thumbstick, there may be a use case of utilizing both thumbsticks for a single purpose. In addition, the user may find it difficult to control two FFB thumbsticks at the same time or easily become skillful depending on the combination of each feedback. We need an additional investigation into bi-manual use of FFB thumbsticks.

As discussed earlier, game players take game interactions in different ways under single and multiplayer situations. Game designers may strengthen their cooperation or competition in multiplayer games when using an FS-Pad interaction. Because we developed only a single-player game for this study, insights into multiplayer interactions may have been reduced.

We also did not deeply consider user fatigue in this study. In the user interview, P2 mentioned that physical fatigue might occur when the player uses an FS-Pad for a lengthy time. Gaming injuries such as a sore thumb, or the so-called gamer's thumb, have been reported with ordinary gamepads [44]. Guidelines on the average strength of FFB, the maximum force level of sudden stimuli, and the proper stiffness for easing the burden on the thumb are needed.

CONCLUSION

We showed that various novel game interaction use cases can be achieved when a gamepad form factor is applied as an FFB device. We built FS-Pad, an FFB gamepad system that can support all interactions presented. We released a 3D printable model, a circuit diagram, and build instructions of FS-Pad to the public, allowing those interested have access to this device. Moreover, we verified that the device has sufficient fidelity to be used as a prototyping tool. Through the user study with game players and practitioners, we found positive reactions and actual needs for new types of interactions when applying FS-Pad. We hope that this research can show the value of haptic feedback, which remains underdeveloped in video game applications.

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