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Force Haptic Interaction for Room-Scale 3D Painting

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Force Haptic Interaction for Room-Scale 3D Painting

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Abstract

Artistic painting involves mastery of haptic interaction with tools. Each tool brings unique physical affordances which determines an aesthetic expression of the finished work. For instance, a pen offers an ability to make a precise stroke in a realism painting, whereas a thick brush or a sponge works perfectly with dynamic arm movement in the abstract art such as action painting. Yet the selection of a tool is just a beginning. It requires repetitive training to understand the full capability of the tool affordance and to master the painting of preferred aesthetic strokes. Such physical act of an artistic expression cannot be captured by the computational tools today. Due to the increasing market adoption of augmented reality and virtual reality, and the decades of studies in haptics, we see an opportunity for advancing 3D painting experiences in non-conventional approach.

In this research, we focus on force haptic interaction for 3D painting art in a room-scale virtual reality. We explore virtual tangibility and tool affordance of its own medium. In addition to investigating the fidelity of a physical interactivity, we seek ways to extend the painting capabilities by computationally customized force feedback and metaphor design. This system consists of a wearable force feedback device that sits on user's hand, a software for motor control and real-time 3D stroke generation, and their integration to VR platform. We work closely with an artist to refine the 3D painting application and to evaluate the system's usability.

Acknowledgements

I would like to express my gratitude to the thesis committee members, Eddy Man Kim, Daragh Byrne, and Kyuha Shim. Although I was in an unusual circumstance of coming back for a single semester from 5 years of the leave of absence to finish my thesis research, they were always supportive and pushed my curiosity to think deeper. Every discussion throughout the course of this research was inspirational, and I could not have done this much with the limited amount of time I had without their mentorship. I also appreciate School of Architecture and Studio for Creative Inquiry for the financial support. Lastly, I am grateful to my family for always being kind and supportive about the decisions I have made.

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1. Introduction

We are engaged with 3D user interface (UI) in our daily lives more than ever due to emerging consumer platforms in augmented reality (AR) and virtual reality (VR). Seeing the trend of UI moving out from desktops, there is an improved capability of directly interacting with spatial virtual environment. It is a natural move to find ourselves exploring virtual space using our arms and hands through tactile and kinesthetic sensors, and haptic feedback will take a larger role in such scenario. We are especially inspired to haptic interactions in painting and will explore deeply the relationships between virtual tangibility and its interaction techniques in 3D painting.

1.1 Background and Motivation

1.1.1 Exploration of New Tangibility in 3D UI

The commercially available personal computers have been largely confined to graphical user interface (GUI) that is controlled by a mouse, keyboard, and touchpad. This is an apt choice for 2D applications with a limited workspace such as writing texts and making a spreadsheet, but its limitation became evident as the 3D paradigm grew and gained its presence in medical simulation, animation/design CAD, and teleoperation. Using a mouse and the windows, icons, menus, and pointer (WIMP) graphical approach in 3D UI requires numerous clicks and unintuitive controls which increases the user's cognitive effort. Instead, the spatial interfaces such as tabletop projection, AR, and VR that enable direct manipulation of a simulated environment have been explored, and the interaction techniques that utilize the rich set of human abilities such as gesture and grasping an object naturally emerged as the optimal solutions (Fig.1). In regard to a wall-sized display demonstrating the improved 3D task controls [1] and the rapid market breakthroughs in AR/VR, we see the spatial interface as a promising computing platform.

Fig.1: Diagram of the interaction choices corresponding to the level of dimension and workspace of UI

However, a commonly raised issue of gestural interaction is that the user does not experience tangibility which comes from manipulating the real-world objects. In fact, handheld controllers are still eminent especially for VR due to its tactility which is being preferred over no haptic feedback. With handheld controllers, the applications are still limited to gaming and other tasks that are achievable with a desktop computer, and cannot unlock its full potential for areas including motor-skill training, artistic crafting such as sculpting and painting, and remote operations. In this research, we explore new tangibility in 3D UI that takes inspirational attributes from the real-world physical interaction and translate it to a tool that enhances the capabilities in spatial interfaces.

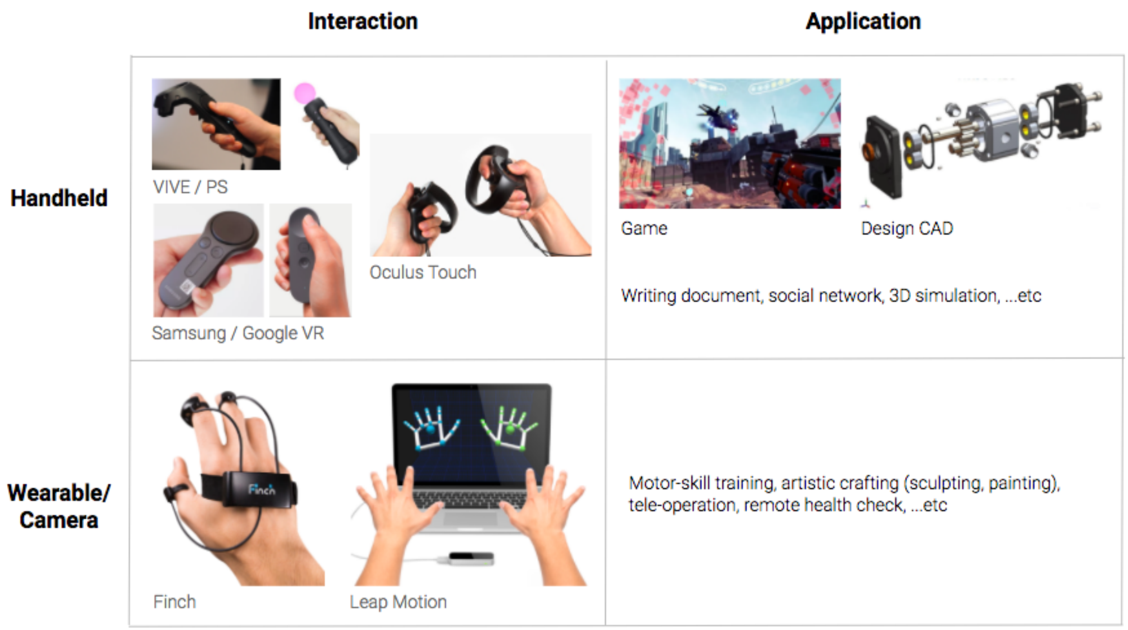


Fig.2: Comparison of potential applications enabled by handheld devices and wearable/camera interfaces

1.1.2 Inspiration from Hand Kinematics and Manipulation

Tangibility comes from the sensation of touch which is categorized into cutaneous (tactile) sensing and kinesthetic (force) sensing. Tactile sensing allows us to feel the surface properties such as texture with a high-frequency vibration, whereas force sensing occurs at the interactions between the hand and grasped object which is used for an object manipulation and the measurement of mechanical compliance. Cutkosky et al. explored the human grasp mechanism which they summarized that the grasp choice is a three-stage process: first an object is identified through a visual cue and a hand configuration is decided, then the finger placement is selected, lastly an appropriate amount of force is applied by each finger and a palm [2]. They observed that the force and motion of hands dictate the grasp choice (cylindrical, fingertip, hook, palmar, spherical and lateral) and we are intrinsically capable of adjusting the hand task as force feedback is applied (Fig.3). In another word, we rely on force feedback to predict how the hand should be configured to achieve the desired goal. One example of application was explored by Wagner which he tested force feedback in remote surgical operation and concluded that it mitigates the mental workload of positioning and controlling a

3D pointer on a simulated body [3]. These studies illustrate the necessity of force feedback in a spatial environment, but it has not been discussed from the perspective of interaction design. Can force feedback be a new interface metaphor for 3D UI similar to the visual and mouse interaction metaphors for 2D GUI?

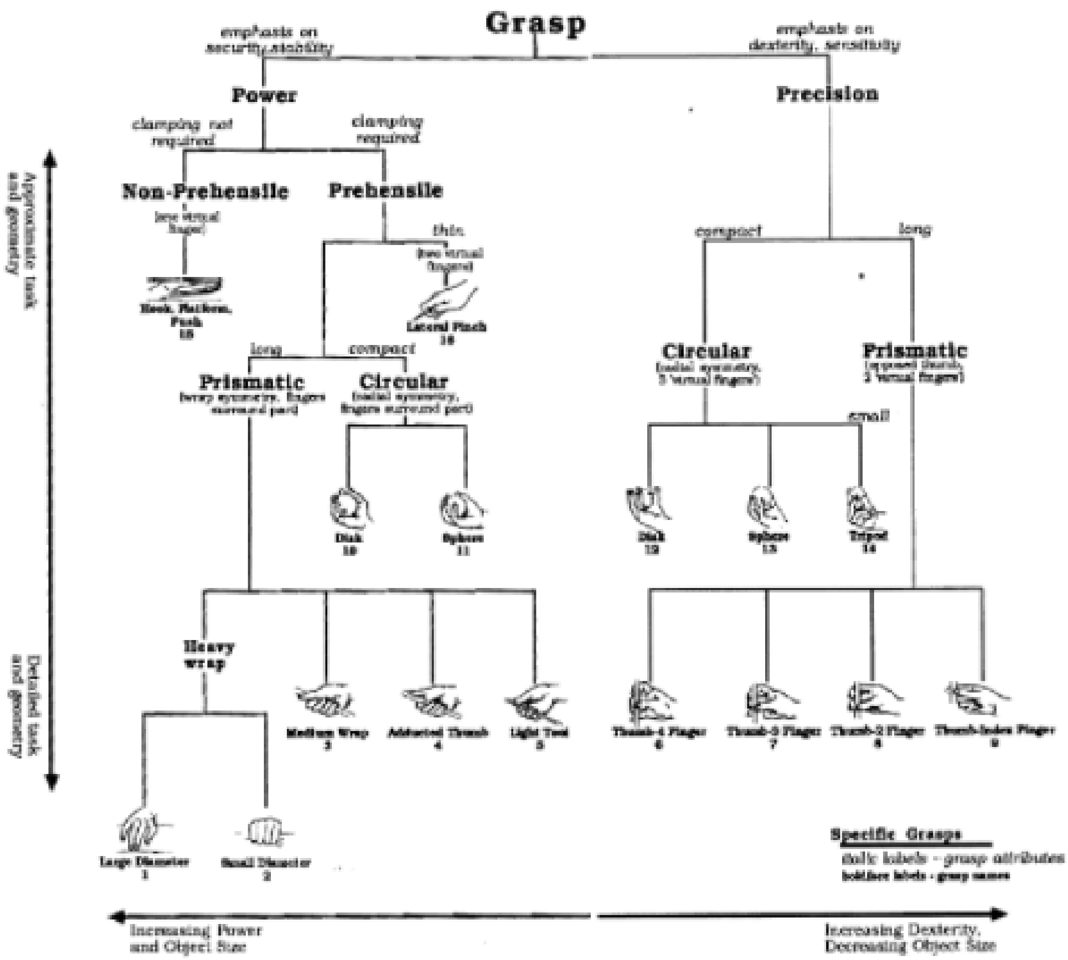


Fig.3: Human grasp patterns [2]

1.1.3 Force Interaction as 3D Interface Metaphor

Interface metaphor is a foundational interaction technique that is incorporated to almost every element of computer systems today to make it easy to use. For instance, GUI is meant to hide all the technical jargons by representing computational commands with visual symbols that are well-understood through our everyday lives. GUI and metaphor have made several transitions since the term was first coined. The early GUI was flat, pixelated, and had no color due to the lack of graphics processor. As the graphical improvements were made, icons became more realistic and three-dimensional with colors and shadows. During this phase, there was a pursuit of realism in GUI which is also termed as skeuomorphism. Fig.4 describes few examples of skeuomorphism that fully replicated the real-world appearance. Apparently, their overly defined realism led to many design inefficiencies such as consuming unnecessary spacing and misleading the user to perceive that an image would function in a certain way although it is just a static image. There was rarely a case where the mimicry of the real-world representation succeeded in the history of GUI. Skeuomorphism gradually faded away and made a transition to flat design which is more an abstract illustration.

Fig.4: Infamous skeuomorphism examples

Tangible user interface (TUI) and its metaphorical interactions were pioneered by Ishii, and his classical work, *Bottles*, beautifully combines the characteristics of a bottle and computational capabilities [4]. He first observed the interactivity of a bottle such as removing/inserting a cork, shaking, and pouring. Key metaphorical features that represent the fundamental affordance of bottles, such as storing a content inside bottles and accessing it by removing the cork, were selected. In order to maintain the consistent perceived affordance, the metaphor and affordance of a physical object need to be seamlessly extended to the computational domain, Ishii says. The system also narrates a story about musical bottles that talk with each other to make a harmonious jazzy track, and triggering them on/off or changing to various tones is as easy as removing/inserting the cork which is a well-understood concept for people of all ages. Lastly, the system truly makes technology invisible by embedding minimal electromagnetic tags that cannot be noticed by users.

Fig.5: Metaphors of physical bottles by Ishii

We believe that simulated force feedback can be another attribute of interface metaphor. Humans are naturally excelled at understanding the level of force feedback associated with a certain physical affordance, and taking an inspirations from the hand grasp mechanism, we believe that metaphorical force feedback can be used to intuitively relate to the real-world phenomenon to achieve desired outcomes. This can be especially useful for the tasks that depend heavily on motor skills. The material properties of everyday objects convey rich information which are optimal resources for defining force feedback metaphors. For instance, the sense of squeeze as a sponge that gradually changes its state and the sense of paddling as a fluidic resistance that generates larger power proportional to the speed of movement. Similar to the skeuomorphism and the bottle metaphor examples, focusing on key physical affordances would lead to a better interface metaphor because the complete replication increases complexity especially in 3D UI and induces confusion. Therefore, keeping the metaphors somewhat in an abstract layer is the essence.

1.1.4 Force Interaction in Visual Art

There is something about art painting that cannot be captured by computational applications. Aesthetic style of painting is largely affected by the tool used and how it is used by an artist. Paint strokes are dynamically adjusted by the amount of force applied to a tool, and humans are capable of remembering such motor skills by practicing repetitively. The sense of pushing a thick brush and scraping paints with a spatchella are few examples of the ways to create unique effects. This is something that can only be accomplished using haptic interaction that occurs between a tool and hand.

Action painting is one genre in which paint is splashed or smeared through the dynamic use of a body. This is an extreme example of how physical interaction dictate the quality of finished work. Fig.6 is a work by Jackson Pollock who often painted with no contact with canvas and relied solely on the momentum of hand, tool, and paint. The finished work is free-flowing, elegant, and organic-looking that cannot be expressed without the harmony of physical act and tools. We see many examples of such from abstract expressionism where the craftsmanship of controlling a tool reflect the finished artwork.

Fig.6: Jackson Pollock, an action painter

Graffiti is another example of painting which is based upon the artistic style of spray. Due to its counter-culture of social expression in public spaces, its style of painting tends to be big, dynamic, and quick which makes spray can a perfect choice. The nozzle of a spray can has an interesting interactivity whose force feedback becomes stronger as pressed further.

1.1.5 Visual Art in Multimedia

Digital painting has been actively explored with artists in room-scale 3D UI. Its ability to draw on mid-air 3D canvas offers painting experience that is unlike others. *3D Graffiti* by Itoh held a live performance with professional graffiti artists to explore new artistic styles in a spatial canvas using a spray can device [5]. *CavePainting* by Keefe et al. and a work by Pick et al. formed evaluation studies on 3D painting with artists [6][7]. Many participants in their studies felt that 3D painting is a compelling medium that enables a new style of artistic expression. The commercial 3D painting app, *TiltBrush*, is offered by Google and it was also experimented with the Disney animators [8].

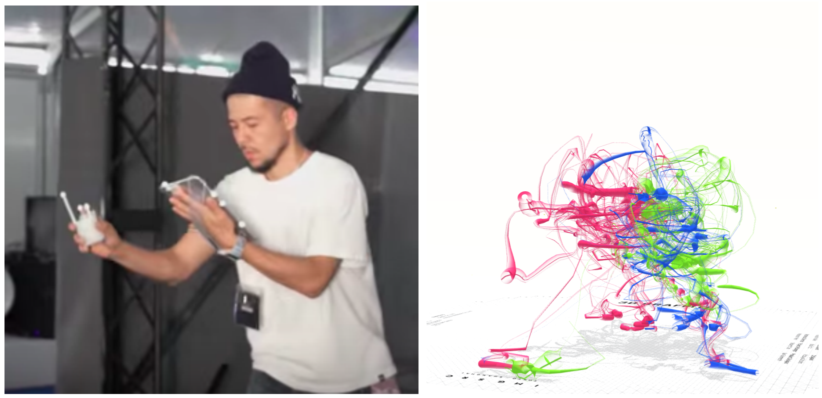
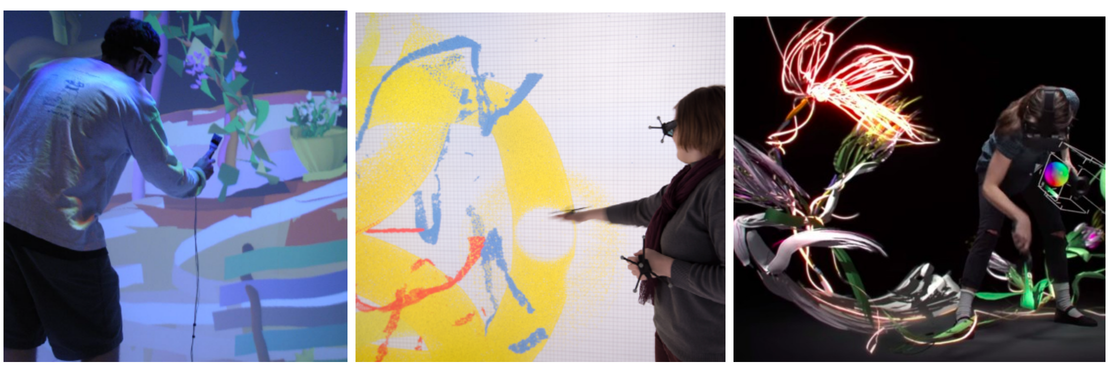


Fig.7: *3D Graffiti* by Itoh



(a)*CavePainting* by Keefe (b)VR gesture painting by Pick (c)*TiltBrush* by Google

Fig.8: VR painting experiments with artists

Graffiti is also used as an experimental platform to convey social messages in a novel way. A notable work by Scheible et al. called *MobiSpray* invited the general audience to make an artistic expression on public spaces using their mobile phone as a painting device [9]. The project is not a mere graphic tool, rather it demonstrates playful ways to communicate in an urban scale utilizing the mobile interaction techniques that make artistic expression easy. Another work by McGookin et al. called *DigiGraff* attaches a projector to a mobile phone to make graffiti-style annotations on the physical environment [10]. The intention of the project was to promote geolocation interaction of social media, and adding the cultural context of graffiti induced the users to participate more freely without being constrained to the conventional style of geolocation tagging. Lieberman et al. built an open-source eye-tracking device that aims to empower ALS patients by enabling them to draw using their eyes [11].

(a)*MobiSpray* by Sheible (b)*DigiGraff* by McGookin (c)*EyeWriter* by Lieberman

Fig.9: Graffiti in multimedia computing

We are particularly interested in translating the rich affordance of painting tools to 3D painting using force feedback haptics. The current state of 3D painting has not addressed the challenge of making painting effects that come from the mastery of tools. Most of the painting apps today use generic-purpose game controllers, but we believe that haptic interaction design plays a central role in it. For instance, the mechanical characteristics of a spray can such as the sponginess of nozzle allows us to dynamically control particles and drips with the adjustment of applied force on an index finger. One potential solution to achieve this is by using a brush or spray-like “props” that mimic their physical affordance, but we explore another approach using a wearable type force feedback device to build affordance uniquely for painting in 3D UI. Throughout the research, we work with an artist to explore building virtual tangibility for 3D painting interface and aim to extend its capabilities using the computational design of force feedback metaphors. Furthermore, we choose VR platform for a room-scale 3D UI which is capable of directly interacting with the virtual scenes in one-to-one scale.

1.2 Research Objective

The main objective of this research is to design and develop the force interaction system for 3D painting in a room-scale VR to explore its own affordance. In particular, we focus on two pillars of sub-objectives that question its affordance from different angles.

1. **Improve fidelity of spray painting using squeeze-like force feedback.**
   Can a sponge-like elastic force feedback contribute on improving the fidelity of spray painting? We hypothesize that such feedback driven by a hands-free device will improve the fidelity of spray compared to non-feedback interface.

2. **Enhance the real-world painting capabilities by metaphorical force feedback patterns.**
   Can force feedback metaphors contribute on enhancing the capabilities of 3D painting? What are the interesting metaphors of the real-world physical interactivity? How should the force interaction be designed and incorporated to 3D UI? Do force feedback metaphors naturally map to already understood concepts? How can a hand force feedback device be designed to achieve a variety of force feedback patterns? We hypothesize that the users will be able to intuitively map force and visual feedback through the real-world experience.

1.3 Contributions

As the outcome of this research, we make three contributions to the community of human-computer interaction (HCI). First is the conceptualization of force interaction for 3D painting. We design interaction techniques that take advantage of force feedback haptics specifically for 3D painting application. Second is the development of wearable force feedback device that is capable of generating multiple interactivity. We make effort on making design and engineering tradeoffs to make the balance of portability and functionality. Third is the generalized knowledge based on the case study with an artist for validating the force interaction for 3D painting.

1.4 Thesis Outline

This thesis is organized in the order of introduction, related works, interaction concept, design and technical implementation, system usability evaluation, and conclusion. Chapter 2 introduces the related works in 3D UI and force feedback haptics to explain the past and the current status of these technologies. We also explain the novelty of this research by investigating the missed opportunities of prior works. Chapter 3 discusses the interaction concepts that we aim to achieve. Based on the concept, we summarize the design requirements of hardware and software system. Chapter 4 describes the system design that implements the interaction concepts. Its underlying technology consists of hardware, software, and their integration. We present the design and engineering decisions involved throughout the process. Chapter 5 explains the methodology for the system usability evaluation and makes an analysis of the results of user tests. We conduct an in-depth case study with a participant whose background is in spray art and more generic study with a participant whose background is in design. The in-depth study involves a contextual interview and 2 sessions of usability tests which the first test compares four modes of force interaction with and without haptics, and the second test asks the participant to perform 3D painting using the system. Chapter 6 concludes this thesis by summarizing the work, reflecting on what has/has not worked well, assessing the system potential, and its future applications.

2. Related Works

As 3D UI proliferates, the necessity of more sophisticated interaction techniques than a mouse, keyboard, and touchscreen becomes prevalent. While wall-scale screen and tabletop projection are gradually entering the market, the portable mobile phones and stereoscopic head-mounted displays that are powered by high-performance GPU and computer vision software are quickly enabling room-scale spatial interactions at scale. In this chapter, we describe the prior works in 3D interaction methods and a series of haptic interfaces that potentially play key roles in room-scale 3D applications.

2.1 3D Interaction Methods

2.1.1 Mouse and Keyboard Interaction

The commercially available personal computers today are still largely confined to GUI controlled by mouse and keyboard for its simplicity and ease of use. The graphical interaction technique using Windows, Icons, Menus, and Pointer (WIMP) presented by Card et al. [12] has been dominant, and 3D UI is not an exception considering the number of settings and controls required for building an interactive 3D scene. Conway et al. presented Alice, a 3D content creation tool that enables animators and novices to describe the time-based and interactive behavior of 3D objects without mathematical calculations and complex graphical computation [13]. Today, an advanced 3D content creation platform is commercially available for developers and hobbyists [14]. Although the mouse is a key component of the 3D control today, it requires extra clicking and dragging due to the hardware constraint. Balakrishnan et al. presented a 3D mouse with rounded bottoms to control two extra degrees of freedom (DOF) by simply tilting it [15].

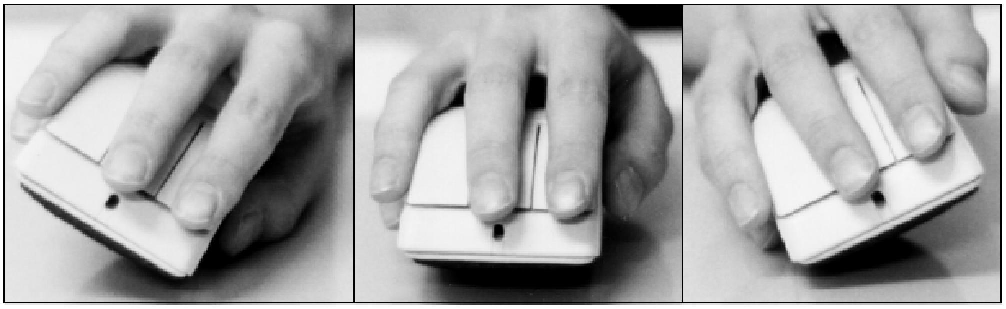
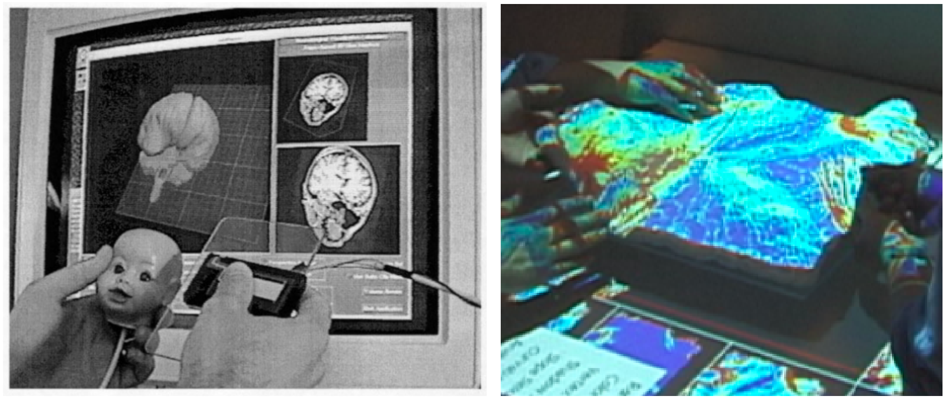


Fig.10: *Rockin' Mouse* by Balakrishnan

2.1.2 Tangible Interaction

As the computer interaction moves out of the desktop, the mouse and keyboard based interaction is no longer applicable. A classical work by Hinckley et al. explored a technique to utilize the everyday real-world object, which they call passive interface props, as an input device to specify spatial relationships of virtual objects for surgical simulation [16]. In specific, a spherical object held in one hand to rotate the simulated model and a rectangular plate held in another hand to specify the position and orientation of a cutting-plane. Unlike the traditional rotation and selection with a mouse, it gives users an intuitive control over simulated objects by real objects. Further studies have been made utilizing deformable physical objects to dynamically shape the simulated objects in three dimensions [17][18]. Fitzmaurice et al. presented various interaction techniques utilizing physical bricks on a tabletop display where the position and orientation of bricks directly affect the simulated objects on a display [19]. This is known to be a pioneering work of tabletop TUI. Patten et al. brought another level of applicability to tabletop TUI by projecting computer-controlled digital information on the physical objects [20]. Piper et al. utilized clay and real-time projection to map the 3D information as the user shapes clay with their hands [21].



(a)Passive interface props by Hinckley (b) *Illuminating Clay* by Piper

Fig.11: Example works from early TUI

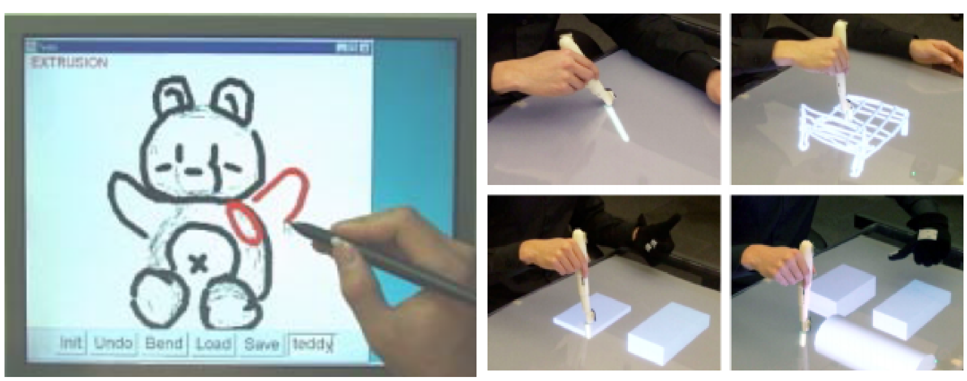
One disadvantage about TUI is that the physical interface is often constrained to a specific task that there is no flexibility of applying a single system to generic use cases. There have been studies that make clever combinations of materials, actuators, and physical computing to achieve customizable interface. Villar et al. proposed a method to freely arrange the input control area using a conducted malleable sheet [22]. By simply plugging the input controls to a malleable sheet that is cut into a preferred shape, the user is able to customize the interface. Harrison et al. worked on a computer-controlled deformable input button that is able to generate a variation of tactility using pneumatic actuation and soft materials while maintaining the calmness of the conventional buttons [23]. *SketchSpace* by Holman et al. turns passive physical objects into tangible interfaces using a depth camera and a projector [24]. Vazquez et al. came up with a novel 3D printing technique for the pneumatic actuation based input controls [25]. The resistance or tactile response of the 3D printed physical controls are programmable, therefore its physical form and interactivity are fully customizable. Lastly, shape display enables to dynamically change the surface form, add interactivity, and generate unique haptic feedback to the user which is one solution to overcome the constraints of the tabletop TUI. The shape display solutions have been proposed in multiple scales ranging from a tabletop to a wearable [26][27].

(a)Customized controls on a malleable sheet by Villar (b)3D printing pneumatic device by Vazquez (c)Shape display

Fig.12: Examples of customizable tangible interfaces

2.1.3 Sketch Interaction

A stylus is a hyper-specific tool for digital writing and drawing that replicates the usability of a physical pen. There have been multiple approaches of generating 3D models from a freeform sketching. Igarashi presented an automated computer graphics technique with sketch-based interaction to design freeform models from 2D strokes using a stylus rather than explicitly specifying its polygonal mesh [28]. Such interaction greatly reduces the amount of WIMP operations for tweaking 3D parameters. Jinha et al. built a pushable pen device that enables to draw three-dimensionally on a tabletop display by pressing the pen against it [29]. It takes key attributes from a spring and a camera tracking to be able to draw 3D strokes in various directions.



(a)*Teddy* by Igarashi (b)*Beyond* by Jinha et al.

Fig.13: Examples of sketch-based interaction methods

2.1.4 Gestural Interaction

The hand gesture is an intuitive form of interaction that we perform daily. When working with a large-display 3D UI or AR/VR, the hands-free gestural interaction that is analogous to the real-world gesture can bring intuitiveness and dexterity to its interaction. An early work by Zimmerman et al. demonstrated a glove type input device that captures gesture, position, and orientation by flex sensor and ultrasonic sensor [30]. It gives the user a direct control over the simulated 3D object with gestures such as picking, grabbing, twisting, squeezing, and throwing. Zigelbaum et al. studied a variety of hand gestures to take an advantage of the human hand dexterity [31]. The computer vision-based gesture recognition has also been studied and now a camera device that is as small as a pen box is commercially available [32][33].

(a)*g-stalt* by Zigelbaum (b)*Leap Motion*

Fig.14: Examples of gestural interaction

2.1.5 Room-Scale Interaction

Display and projection based 3D interaction have limitations since virtual objects cannot be manipulated spatially. This especially applies to gestural interaction whose input actions do not intuitively match the scale of the visual feedback on a screen. Room-scale interaction enables direct manipulation of 3D objects in the form of AR, VR, or projection. The next phase of spatial interaction might be digital information projected everywhere. Wilson et al. designed the system for a room-scale projection that uses multiple depth cameras and projectors [34]. The projection is illuminated to every table and wall which allows the user to control multiple projections simultaneously, and sometimes “pick-up” and “drop” virtual information from one place to another. Similarly using multiple projectors, *Mano-a-Mano* is a spatial augmented reality that creates a device-less shared AR space [35]. With these techniques, the user has a direct one-to-one interaction with the virtual environment rather than mapping your movement on a screen.

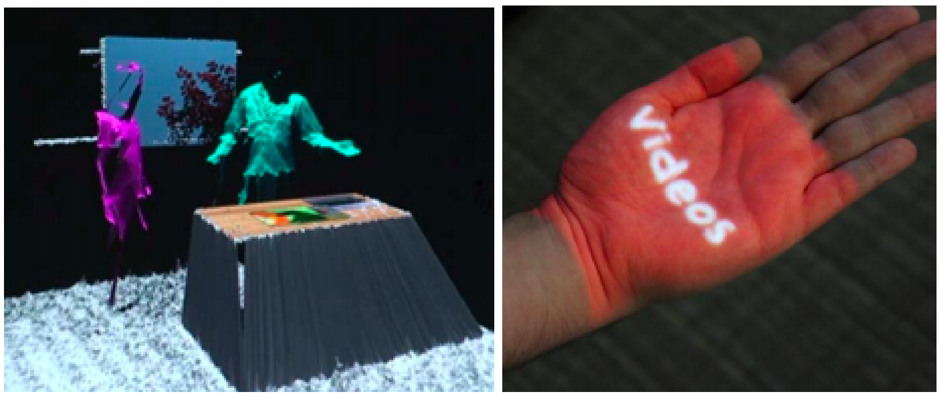
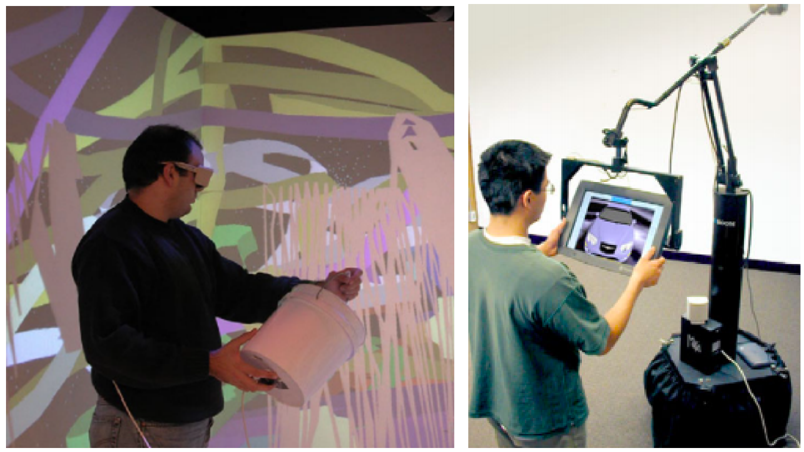


Fig.15: 3D projection techniques by Wilson

AR and VR are commonly used platforms for a room-scale interaction as well. *CavePainting* by Keefe et al. created a fully immersive Cave environment specifically for a 3D art [7]. The project aimed to reproduce the effects of 2D brush strokes in a 3D scene and used physical props such as brush, bucket, and paint cups as painting interfaces. Pick et al. worked on a hand-gesture controlled VR artistic drawing system [6]. They introduced several visual effects triggered by different modes of hand gesture. *Boom Chameleon* utilized a panel display mounted on a tracked mechanical boom as the window to explore one-to-one scale 3D environment [36]. Itoh exhibited a one-to-one scale mixed-reality collaborative 3D graffiti tool for artists [5]. Using motion capture cameras, it created a 5m by 5m by 2m virtual canvas in the physical environment, and the interactions were designed upon the real-world graffiti and painting style. Today, similar 3D drawing and design systems for VR are commercially available [8][37][38].



(a)*CavePainting* by Keefe (b)*Boom Chameleon* by Tsang

Fig.16: Examples of room-scale interaction techniques

2.2 Haptic Interfaces

One-to-one scale interaction in virtual environment enables new applications that involve movement and dynamic actions. The sense of touch has been an active field of research in HCI to support those use cases. In this section, we present various haptic interfaces, their applications, and the latest studies.

2.2.1 Tactile and Pseudo Haptics

The most convenient and widely accepted haptic interface is tactile (vibratory) feedback which is embedded inside most of the portable computing devices today such as mobile phones and game controllers. Interesting applications ranging from gaming to education have been presented to measure the impact on the user's cognition. *Hand-to-Hand* by Pittera et al. is a two-handed vibratory controller that generates an illusion of the simulated object movement from one hand to another [39]. Such illusion of touch is also called pseudo haptics which makes a good combination with VR experiences. Yannier et al. applied vibratory feedback to enhance the children's readings and concluded that the chapters of the story with haptic feedback were better comprehended [40]. Bau et al. explored the augmentation of custom tactility on physical objects by electrovibration-based feedback [41]. Another interesting category is a mid-air haptics that is enabled by an ultrasonic transducer array. *UltraHaptics* by Carter et al.

demonstrates multi-point haptic feedback system which requires no device to be worn or held [42].

(a)*FeelSleeve* by Yannier (b)*REVEL* by Bau (c)*UltraHaptics* by Carter

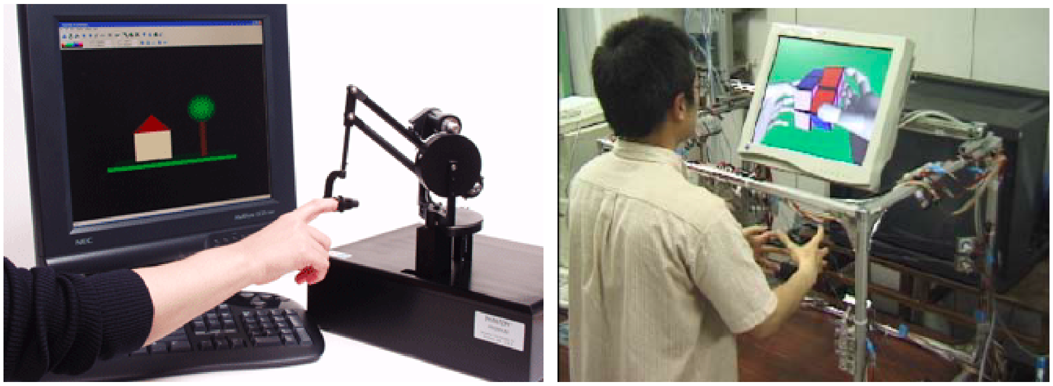
Fig.17: Examples of tactile haptic techniques

2.2.2 Force Feedback Haptics

Unlike tactile feedback that is commonly achieved by a high-frequency vibration, force feedback reproduces the directional forces between a hand and an object using an actuator. In this section, we discuss two major categories of force feedback device - grounded and wearable types.

2.2.2.1 Grounded Devices

Commercially available force feedback device that is most popular today is the linkage-based system which has a pen attached to a robotic arm [43][44]. The advantage of the grounded type is its ability to accommodate multiple high-torque motors to achieve multi-DOF with a realistic amount of force feedback. Another approach using a cable and a pulley has been proposed by Sato [45]. His SPIDAR system focuses on a free-handed manipulation which can be scaled to be used in various settings (e.g., sports event installation). However, it consumes a considerable amount of space which makes it hard to be commercialized.



(a)*PHANTOM* (b)*SPIDAR* by Sato

Fig.18: Examples of grounded force haptic device

The linkage-based force feedback haptics has been actively applied for training people to perform real-world tasks [46]. One example is the virtual workbench for training electronic technicians. Without the need of a full electronic setup, the system allowed the technicians to operate switches and use a virtual multimeter with a probe applied on a simulated 3D circuit board. Another example is the simulation of the surgical tasks based on a realistic anatomical 3D models. The force interaction capabilities in such scenarios are highly effective in training and evaluating the user's sensorimotor skills. Another interesting experiment was made by Basdogan et al. investigating the collaborative 3D manipulation using force feedback device [47]. Keefe et al. studied sketch interaction technique that is aided by force feedback haptics (*PHANTOM*) for drawing the controlled 3D curves [48]. They address the problem of inability to precisely control the drawing strokes in mid-air by using force feedback as a guide.

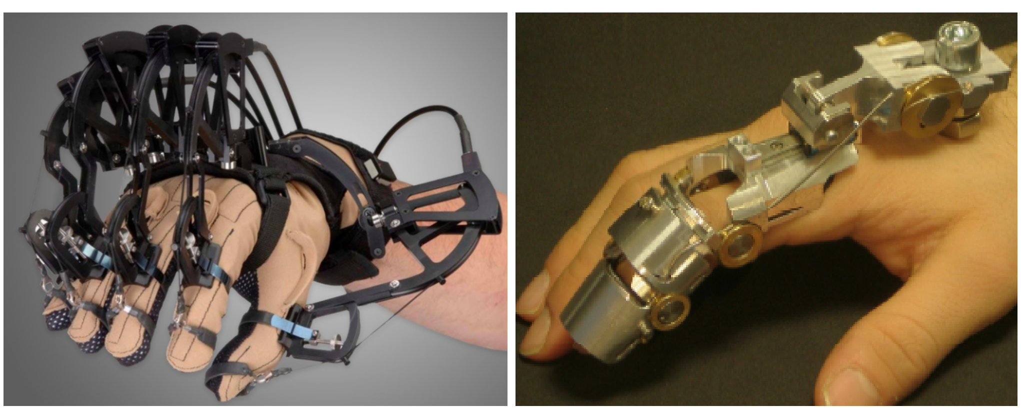
PHANTOM used for (a)surgical simulation (b)precise 3D sketching

Fig.19: Example applications of grounded-type devices

2.2.2.2 Wearable Devices

The wearable force feedback device is beneficial in freely moving fingers enabling a full advantage of hand dexterity. As the trade-off, making the device compact to fit on a hand is challenging. Although we will not be delving into the mechanical engineering of a hand exoskeleton, we touch on few of the related works that we studied for making appropriate design choices. We focus on the wearable devices that provide kinesthetic stimulation rather than the fingertip devices that merely generate cutaneous stimulation [49][50].

The primary category of the wearable devices is the exoskeleton which is commonly applied to rehabilitation. In general, key mechanical features that affect the design choice are actuation type, force transmission method, number of DOF, number of contact points per finger, and number of fingers. A rule of thumb is that as the number of DOF, contact points, and fingers increase, the mechanical complexity and the physical size also increase. A commonly used approach is the motor driven linkage system pulling each contact point of the finger from the top [51][52]. The disadvantage about this design is that the linkage becomes longer if accommodating enough finger motion space. Chiri et al. made the design compact by using a cable to directly rotate the device joint which is aligned to the wearer's hand joint [53].



(a)*CyberGrasp* (b)Design by Chiri

Fig.20: Examples of high-end wearable devices

The new category of portable force feedback device is emerging to meet the demand of VR. Bakker et al. presented a low-cost haptic device that provides both tactile and force feedback [54]. Rather than mounting the device on top of the hand, it places two rings for the index and middle finger which are connected by guide rails to enable squeeze motion. Although its force feedback is simply a brake, a combination of tactile and force feedback enabled smooth 3D design interaction. Choi et al. demonstrated the four fingers design with the brake force feedback using DC motors [55]. Another work by Choi called *CLAW* combines tactile and force feedback capabilities into a single handheld VR controller [56]. *NormalTouch* by Benko et al. presented a handheld 3-DOF force feedback device for VR [57]. *Haptic Links* is a two-handed force feedback device that connects two handheld VR controllers with a variable stiffness chain [58]. Gu et al. presented the exoskeleton VR interface commercially [59][60]. All of the above devices are covered by rigid bodies which tend to make the devices bulky and intrusive. A more compliant approach is using soft materials and Jadhav et al. presented a force feedback glove that is built with soft linkages and cables driven by a fluidic actuator [61]. It is specifically designed for VR to create the sensation of clicking.

(a)Force haptics for spatial design tasks by Bakker (b)*Dexmo* by Gu (c)*NormalTouch* by Benko

Fig.21: Examples of portable force feedback devices for VR platform

2.3 Missed Opportunity

Although a number of wearable and handheld hardware designs for force feedback haptics have been presented, we have not yet seen the design of force interaction for a specific application that goes beyond the generic use cases. It is also argued by Keefe et al. [48] that most of the works focus on simulating realistic surface contact forces rather than using force feedback as a guide to assist 3D interaction. The early works by Salisbury investigated the impact of grounded linkage-based haptics on surgical simulation and motor skills training, but nothing in a room-scale 3D UI or VR with hands-free force feedback interfaces. Our goal is to define the force interaction concepts for room-scale 3D painting and to execute field works with the practitioners to refine and evaluate the system usability.

3. Force Interaction Design

In this chapter, the concept of force interaction and the methodology of the system development are explained. Furthermore, 3D painting application and its interaction techniques are introduced.

3.1 Concept Definition

Traditional input devices have been confined to a two-states control of on-off and have not utilized the adjustment of force to make a variable control. As for gesture interaction, there is no tangible feedback for the user to acknowledge that the action has correctly accomplished. This creates an additional lag during the interaction process where the user needs to visually confirm to validate the action. The concept behind force interaction is to virtually create physical interactivities with variable force feedback to guide the user's 3D input control. The user experiences the series of tangibility that is well-understood through the real-world interactions such as squeezing, clicking, and grasping. The system is also programmable that a variety of feedback can be achieved with a single device. This mitigates the hassle of customizing hardware for each feature. We took advantage of the notion of interface metaphor to uniquely map metaphorical virtual tangibility to everyday experiences in order to facilitate the 3D controls.

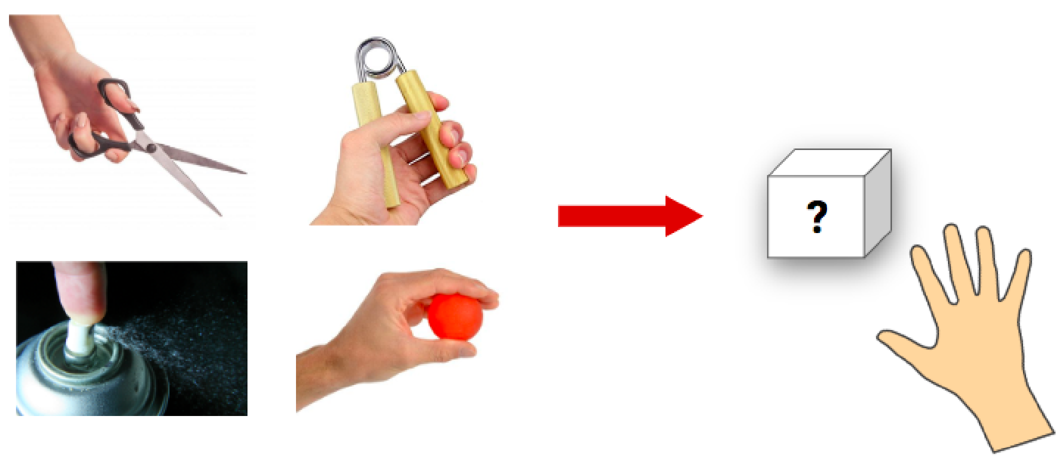


Fig.22: High-level concept of incorporating multiple modes of force interaction

3.1.1 Categorization of Everyday Interactions

There is a number of interaction patterns that occur between a hand and object. To name a few: grasping, throwing, cutting, pushing, pulling and rotating are the hand interaction that we utilize everyday. We choose to categorize them by the patterns of change in force feedback applied to a finger, and we found out that it can be distinguished into 3 generalized modes: constant, transitional, and instantaneous. An example of the constant mode is grasping which you apply a constant amount of force to maintain an object grasp. The transitional mode changes the amount of force depending on the position or velocity, and the instantaneous mode makes a sudden drop or gain in force feedback to create radical bumpiness. These physical interactions can be visualized in graphs as illustrated in Fig.23. In general, force feedback varies with respect to the position or velocity (this research specifically focuses on the interactions of a finger).

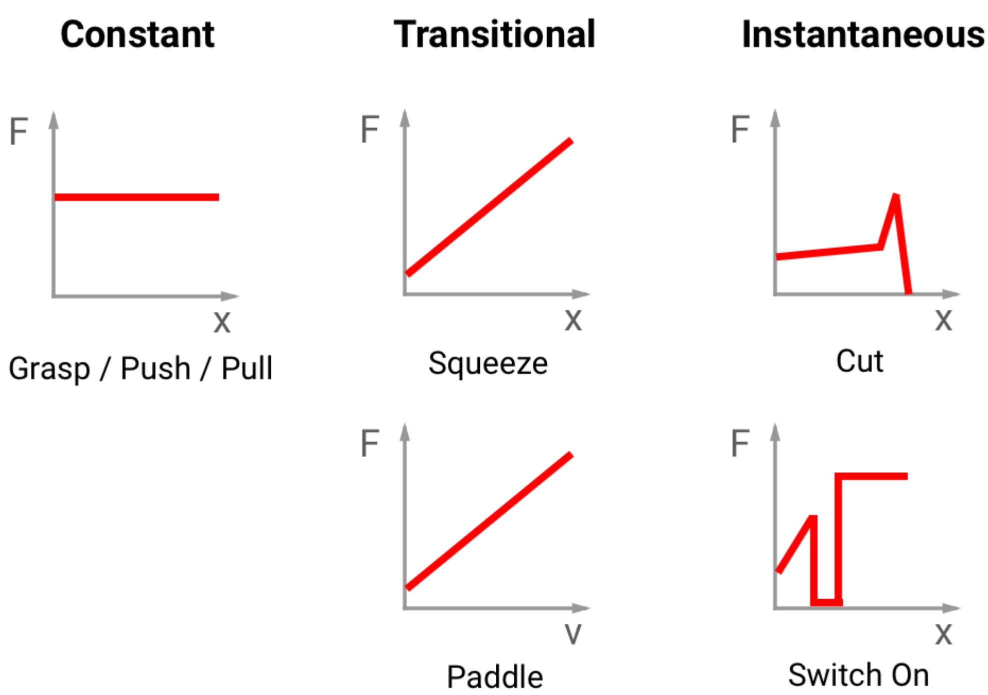


Fig.23: Categorization of physical interactions

3.1.2 Extending Virtual Controls Using Metaphor

Similar to how metaphor is defined for GUI, we believe that it can also be applied for force feedback to extend the capabilities of the real-world interactions. For instance, the grasp mode can be a metaphor of maintaining a state and an instantaneous strong force feedback between an index finger and a thumb can be used for creating virtual objects of a consistent size. Another example is the sponge-like squeeze mode as making gradual changes such as color and volume. The usage of sensorimotor skills can be advantageous in a room-scale 3D UI where the workspace is large and requires haptic exploration to effectively make controls. We believe that an excessive replication of physical affordance is not necessary as introduced in section 1.1.3. Rather, a simple and intuitive metaphorical mapping of interactions is more important and unnecessary realism should be avoided.

3.2 Methodology

Force interaction is achieved by a hardware that physically generates force feedback and a software that computes and controls an optimal force feedback in real-time. We introduce the design approach of the system that was selected to demonstrate the proof-of-concept prototype.

3.2.1 Haptic Interface Device

Contrary to a high-frequency non-grounded vibrations that stimulates cutaneous sense, force feedback is a kinesthetic stimulation that applies resistance against movements. How this is achieved in general is by mechanically pulling a finger against its motion with an actuator as illustrated in Fig.24. In the real-world, force feedback is applied to various directions depending on the grasp choice made, but mechanical actuation requires a single actuator per direction, therefore accommodating multiple directions can add up its complexity quickly. In this research, we focused on applying force feedback only on an index finger since it is the most commonly utilized finger for hand manipulation. Furthermore, we made design choices to accommodate a variety of force feedback modes that are described in Fig.23.

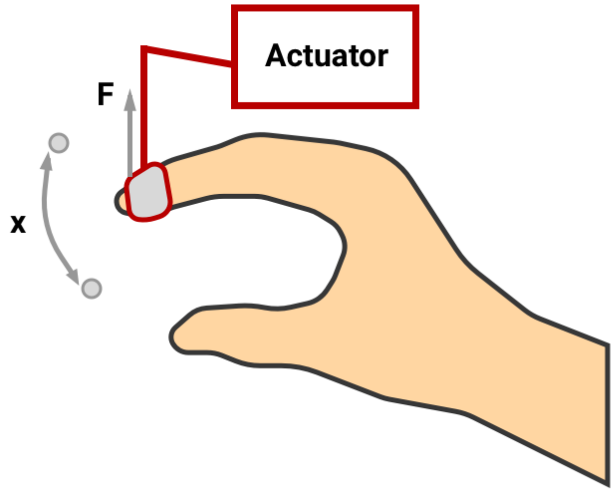


Fig.24: Force haptics mechanism (F: force feedback, x: distance of finger movement)

3.2.2 Programmable Physical Interactivity

One powerful feature about the system is an ability to customize the force feedback and to employ different interactions as the user interacts in a 3D space. This is achieved by sensing the finger motion, controlling an actuator with high-frequency signals, checking the actual amount of force applied, and making a feedback-loop to optimize the control. With respect to the finger position or velocity, the amount of force controlled by an actuator is computed and applied. As described in Fig.23, the customized force feedback patterns can be programmed and tuned in a preferred way.

3.2.3 Scheme for Force Interaction in a Room-Scale 3D UI

An overall scheme for force interaction in a room-scale 3D UI is described in Fig.25. We integrated the force interaction scheme to a spatial camera tracking system and a 3D application that the user experiences. A room-scale spatial interaction is an important part of this research as this is where hands-free haptic exploration becomes critical and new 3D applications emerge.

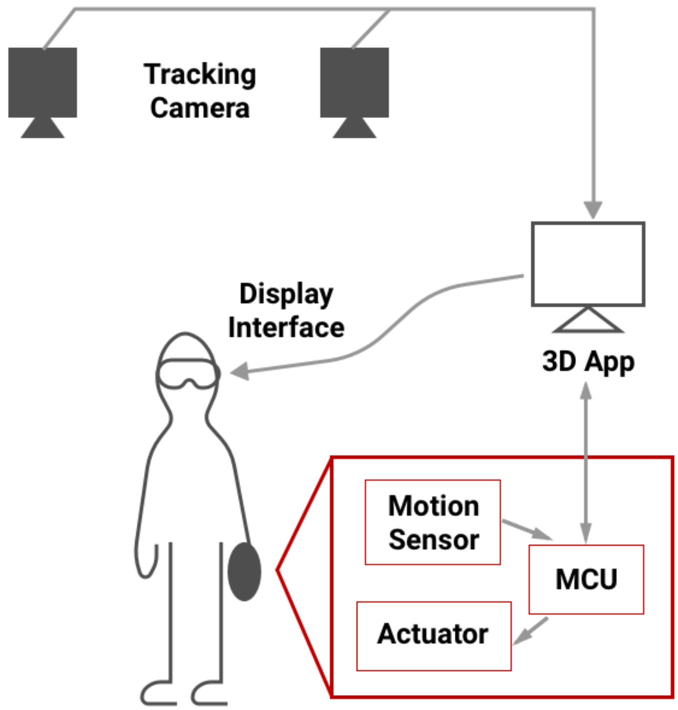


Fig.25: Design scheme of the system

3.3 Force Interaction Design for 3D Painting

The goal of this research is to translate the force interaction concept to a 3D painting tool. We are particularly interested in achieving two types of affordance: fidelity of an existing physical tool and metaphorical physical interactivity. We selected spray can as the tool to reproduce its fidelity. We started from studying the physical interactivity of a spray can and how an artist works with a spray through a contextual interview, and came up with force interaction techniques specifically for 3D painting.

3.3.1 Spray Can Analysis

What makes unique about a spray can is the mechanical compliance of a nozzle. It is not only squeezable in a single direction, but can also be minimally pressed in different angles which adds interesting randomness to its interactivity. In general, further it is pressed, larger the stroke becomes. The nozzle has a large force feedback from the beginning and the range of press is small. The selection of a nozzle is equivalent to choosing a brush type, and the customization of nozzle is critical in making the desired stroke width, effects, and volume. Fig.26 shows three types of nozzle [62]. Each type offers slightly different contact, and the spray volume ranges from “thins” to “super fats”. Fig.27 describes how varying nozzle and insert types make different spray patterns such as softer inner volume and harder edges. Furthermore, there are spray cans with varying levels of pressure. Low pressure type is optimal for thinner and cleaner lines, and high pressure type is to extract the highest volumes of paint.

Fig.26: Types of spray can replacement nozzles [62]

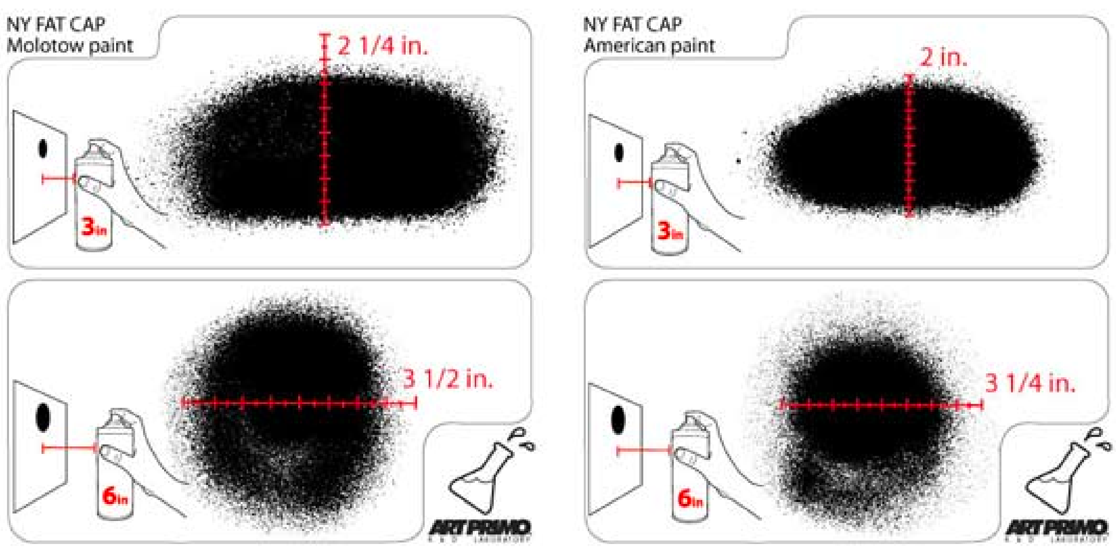


Fig.27: Spray patterns [62]

3.3.2 Contextual Interview with a Spray Paint Artist

We also ran a contextual interview with a spray artist to understand how the tool is used in an actual practice. The interviewee was allowed to use a spray and any other painting tools if preferred. Throughout the observation, he used a spray and a spatchella with various color paints for making an artwork. The first and the foremost insight we found was that haptic interaction was part of the painting process. The interviewee thinks different haptic interaction creates different aesthetic style and he chooses tools with the right tangibility for every artwork. For instance, when making drastic changes to strokes, he chooses a more rigid spray nozzle, whereas when making soft strokes, he chooses a generic one. He especially likes 3-inch thick brush rather than precise ones, and the used brushes are even better because they bring out the characters of bristles. Another observation was that the spray effect depends on the combination of press level, distance from canvas, and angle. We took inspirations from this study to identify the interaction techniques specifically for spray painting.

3.3.3 Force Feedback Patterns for 3D Painting

We defined four modes of force interaction as described in Fig.28. The first mode is “squeeze” which aims to achieve the fidelity of a spray can. The amount of force increases in proportion to the finger position, and the line similar to Fig.23 is programmed to reproduce the real physical interactivity. The second mode is the opposite of squeeze which we call it “custom” mode. It generates the maximum force at first and gradually decreases. This interactivity does not exist in the real environment, but one of our interests is to enhance the capability of physical interaction through customized virtual tangibility. The third category is “grasp” mode which makes a metaphor of holding an object as making a constant stroke thickness with a constant force feedback. Lastly, “click” mode makes an instantaneous feedback drop which tries to achieve drastic strokes that we often see in action painting. The user can rest his finger on an initial feedback and apply a strong force to release the feedback. In addition to all the above modes, the stroke thickness responds to the speed of motion and it gets thinner as the user makes a faster stroke which is an important technique in the real painting as well.

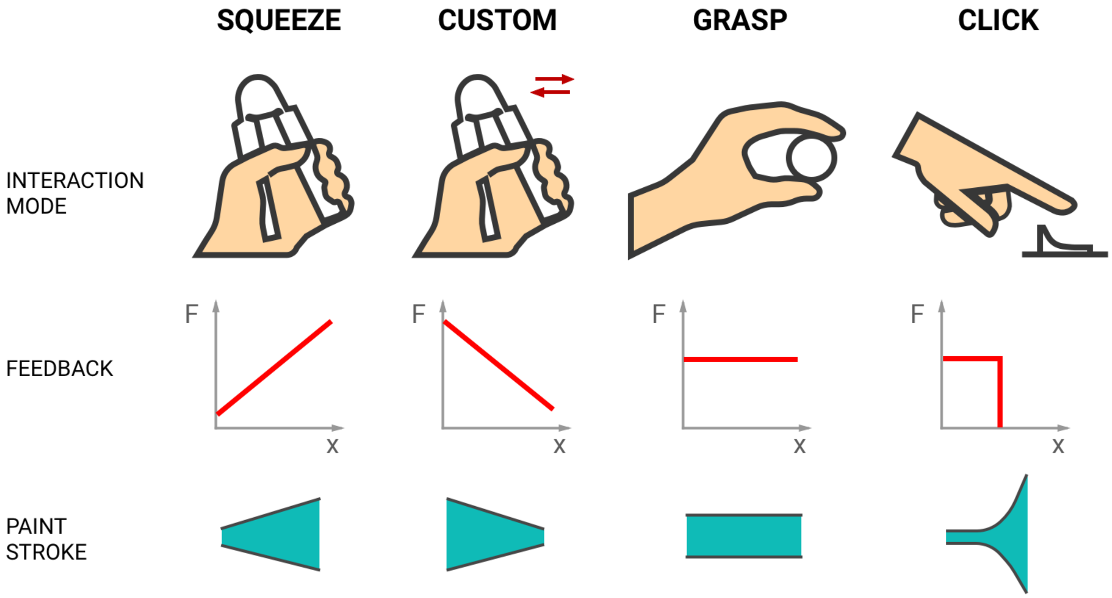


Fig.28: Force interaction patterns for 3D painting

4. Design Engineering of Prototypes

In this chapter, the design and technical implementations of the system are explained. In large, there are three components to the system - electro-mechanics, 3D software, and VR integration.

4.1 Design Criteria of the System

Based on the force interaction concept from the previous chapter, we first summarize the design criteria of the system. It is essential to address them in order to capture the uniqueness of the research. The criteria are categorized into three groups - interactivity, device, and scale.

1. **Interactivity: customizable force feedback.**
   We explore various force feedback patterns to define tangibility in virtual space rather than simply reproducing the sense of grasp or touch. This especially affects the design decisions of the device such as backdrivability, amount of force, and response time.

2. **Device: wearable and portable.**
   To fully utilize the dexterity of hand and finger movements, we focus on designing it wearable and hands-free. With handheld devices, the user experiences additional force feedback of a rigid object inside the palm which interferes with the main interactivity and intrudes the natural haptic sensation. Furthermore, because the artists move around the space and make dynamic hand movements, the device should be non-intrusive and portable.

3. **Scale: one-to-one room-scale.**
   The need of haptic exploration becomes critical in a spatial virtual environment where direct manipulation of virtual objects is possible, and we design this virtual spray painting system specifically to meet the needs of visual artists who work with physical tools in the scale of a wall or a room. The painting actions and process are also part of their artworks which the haptic interaction plays the central role.

4.2 Electro-Mechanics of Haptic Interface

The wearable design can be challenging due to the inconsistent form and size of our body. Our hands are especially complex considering that we have five fingers with multiple joints that in combination enables dexterous object manipulations. In addition to the final model, we introduce the process of designing a wearable electro-mechanics that accompanied countless design and engineering trade-offs.

4.2.1 Design Considerations

Fig.29 summarizes important considerations for designing a haptic interface in this research. First, there are mechanical characteristics that are deeply associated with creating a natural and customizable feedback. The device should be backdrivable so that there is nearly no resistance when it is inactive, and an ability to generate feedback in both directions increases the variation of interactivity. Furthermore, the device should maintain low mass, inertia, and friction to prevent any unwanted feedback that would degrade the fidelity of interaction. Backlash that occurs between the teeth of gears or belts can create a dead-zone that leads to inconsistency with visual interaction. Improvement of such performance allows it to naturally adapt to the user's body, but it often entails a compromise on size. Making a strategic balance of the feedback efficiency and the device size is critical. Another element that affects the size is the number of fingers and contact points the force is applied to, but we choose to stay with 1 finger, 1 contact point, and 1 DOF per contact point since the immersion that comes from having more is not a primary goal. Lastly, an ergonomic form should be considered in order to generalize on a variety of hand sizes. We experiment on using soft and adjustable materials to keep the design simple.

Criteria	Design Considerations
Customizable and smooth interactivity	- Backdrivability - Bi-directional movement - Low mass, inertia, friction, and backlash - Enough amount of force feedback

	- High response time - Enough range of finger movement
Wearable on hand	- Small actuator and electronics that fits on top of a hand - Minimum of 1 finger, 1 DOF, 1 contact point - Fits to a variety of hands

Fig.29: Summary of design considerations

Because the force feedback devices require to physically generate a certain amount of force to make the interaction realistic, the selection of an actuator dictates the level of performance and potential design choices, therefore it is the first decision that needs to be made. As mentioned in the previous chapter, there are actuation methods such as pneumatics with soft materials, hydraulics, and shape memory alloy, but each has its own downside that critically affects the achievement of our criteria. A pneumatic actuator is not good at translating air pressure into a precise output which could create inconsistent feedbacks. The hydraulics tend to be large and can be considerably expensive to fit on a hand. A shape memory alloy has a slow response time and consumes a lot of current that it is not an apt choice for haptic implications. We chose a DC motor as an actuator due to its instantaneous response time, high torque, controllability, and compactness, and we discuss further in the following section the process of deciding the force transmission methods, motor brand, and wearability design.

4.2.2 Process

We first implemented the simplest mechanism with a DC motor and a direct capstan drive. The pulley on the motor is directly driving the second pulley through a stainless steel cable, and the rotary motion is converted into a linear motion using a ball joint. The radius of the pulley is adjusted accordingly to provide enough range of finger motion. To make the prototyping easier, we placed the actuator inside the palm similar to a handheld controller. In this experiment, we focused on understanding the alignment of joints and the amount of feedback felt on an index finger. The joints are aligned at the root of the finger (carpometacarpal joint) which we predicted to be more comfortable than controlling at other finger joints. The index finger was constrained to a fixed pose due to 1 DOF, but force feedback was stable even though it was tested with a low-quality hobby motor. We also found the capstan drive challenging due to its mechanical slip for not perfectly wrapping the cable. Fully working prototype is described in Fig.30.

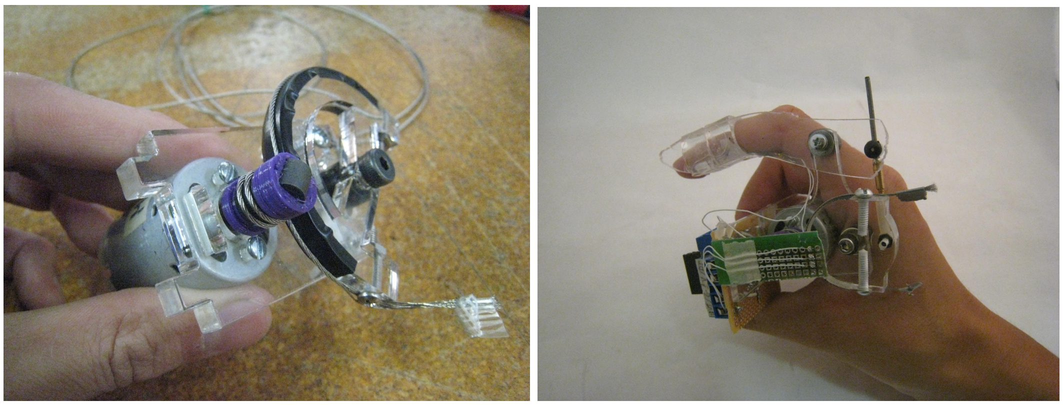


Fig.30: Prototype 1

The second prototype focused on placing the actuator and the direct drive mechanism on top of the hand. The 4-bar linkage translates the movement into a single direction rather than allowing in multiple directions and force dissipation using a ball joint. Furthermore, we experimented applying force feedback on perceptual joint of the index finger since a lot of hand manipulations occur at the fingertip and the entire finger movement can be tiring. We also tried fixing the thumb in order to create a better feeling of pinching.

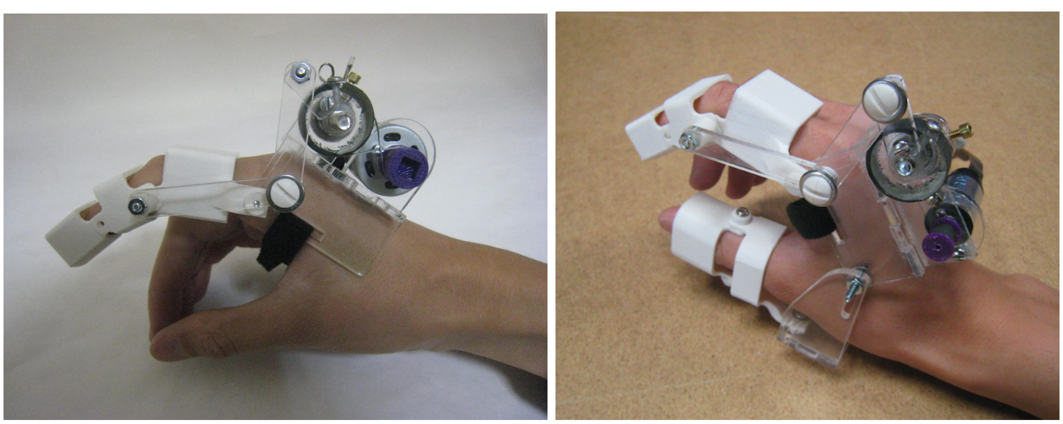


Fig.31: Prototype 2

Cable capstan drive is a well-suited option for a force feedback device due to zero backlash, a negligible amount of friction, and backdrivability. However, the cable needs to be perfectly wrapped around the pulleys or else the cable slips off and creates unnecessary resistance. It required a lot of maintenance to wrap in spirals around the input pulley and to adjust the right cable tension that we decided to explore alternative force transmission methods. Belt drive is a commonly used technique for effectively transmitting force. We also employed Maxon A-Max 26 motor which is a high-quality motor with no magnetic cogging, low mass inertia, and the stall torque of ~60mNm. Compared to it, Jameco motor only had a stall torque of 8mNm and had cogging that interfered with the motor feedback. The belt drive worked well and the effect of backlash was tolerable, but the motor oriented sideways which was consuming extra space and was uncomfortable on the hand.

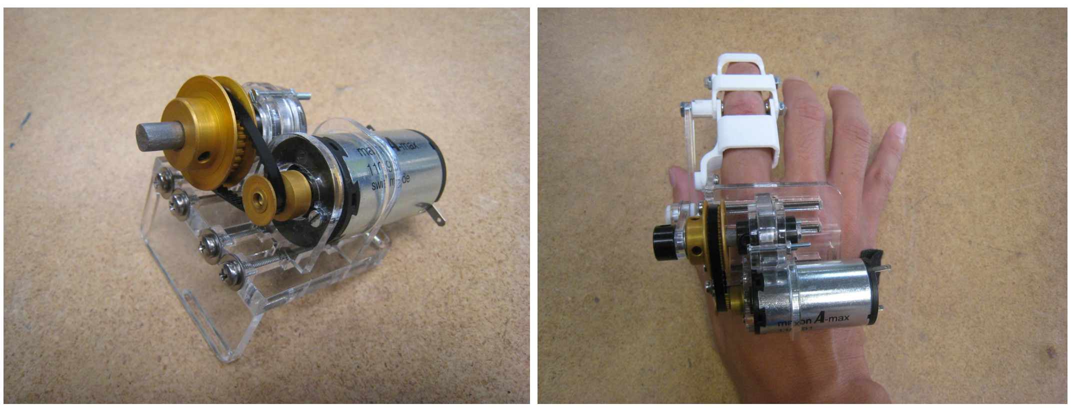


Fig.32: Prototype 3

We also worked on a prototype using tendon mechanism which utilizes a cable to apply force rather than using rigid linkages. Tendon mechanism has a significant advantage in reducing rigid mechanical components and in providing flexibility to its mechanical alignment. One approach we tested was pulling the fingertip upward with slide-and-revolute joint, but this was single-directional. We tried wrapping a cable directly to the side of perceptual joint to make it bi-directional, but the installation was extremely challenging that we decided to take a simpler approach for now.

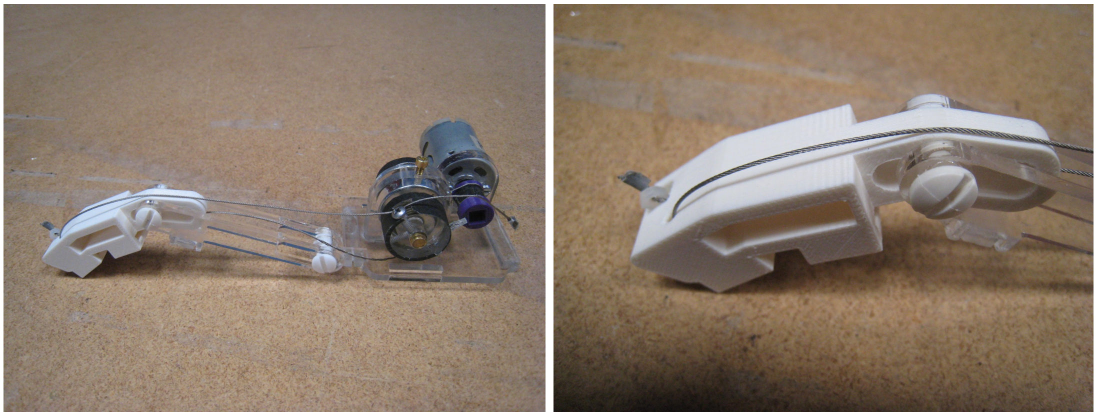


Fig.33: Prototype 4

4.2.3 Final Model

Our final model uses a DC motor and a single set of gears. The bevel gear is used for its ability to change the angle of rotation axis which makes the actuation unit more compact. Furthermore, bevel gears are easy to install and have no risk of slipping. Although we need to compromise on the backlash, having a more stable actuation and to fit on top of the hand have higher priorities for making experiments. A smaller Maxon motor, A-Max 22, which has a stall torque of ~50mNm is selected. Approximately 10N of force occurs at the interaction between a finger and an object, and the stall torque of 50mNm~80mNm is an apt choice considering that there is a dissipation of force throughout the transmission. As described in Fig.34, a flex sensor is packaged with stretchable silicone and is attached on top of the index finger. The custom electronics board is designed in order to compactly place it next to the actuator. Lastly, silicone cushions and Velcro are used to accommodate wearability. The silicone is attached underneath the base of the actuator in order to prevent rigid contact with the skin and to adapt to the bumpiness of different user's hands. The Velcro at the fingertip is movable and can be tightened to adjust to the wearer's finger length.

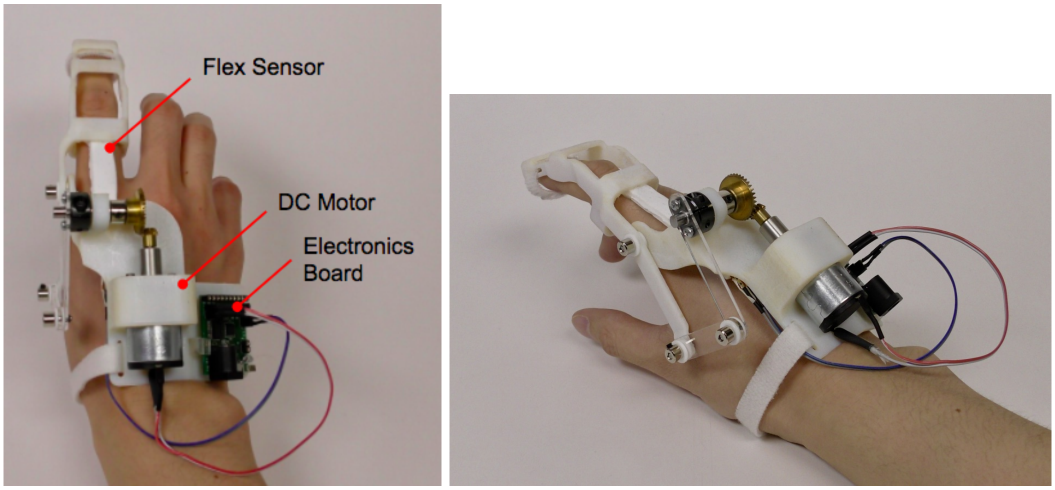


Fig.34: Final model of the wearable force feedback device

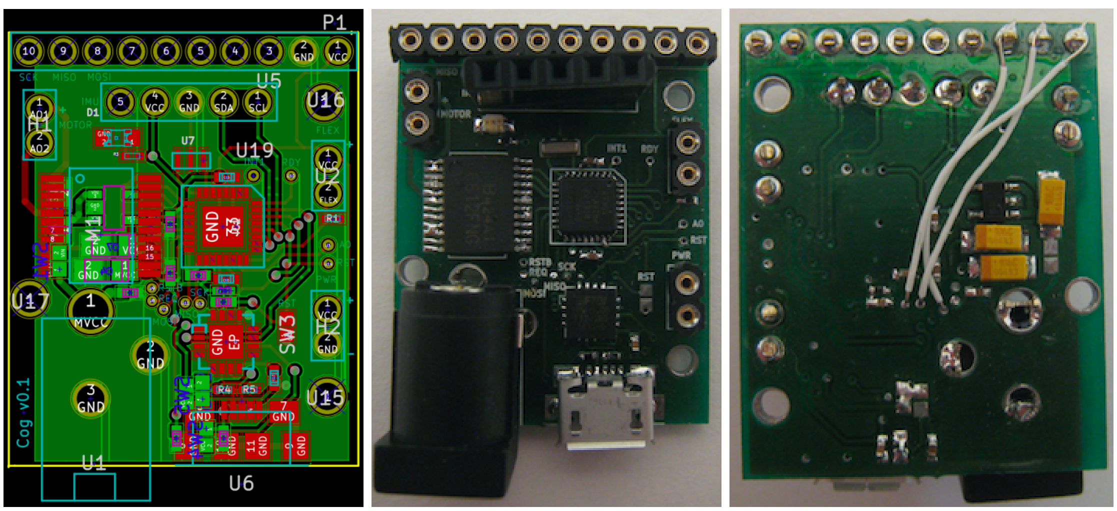


Fig.35: Custom electronics board

We also employed a parallel 4-bar linkage system to transmit force to an index finger. The parallel linkage is often implemented to the kinematics of grounded force feedback devices for its ability to minimize inertia and maximize the amount of transmitted force. Links l1 and l3 are placed in parallel and the angle beta is adjusted to be 90 degrees at relaxation position in order to maximize the force transmission. Furthermore, links l1, l2, and l3 are simulated to accommodate enough range of finger movement by preventing to encounter the dead-points too early for links l1 and l3.

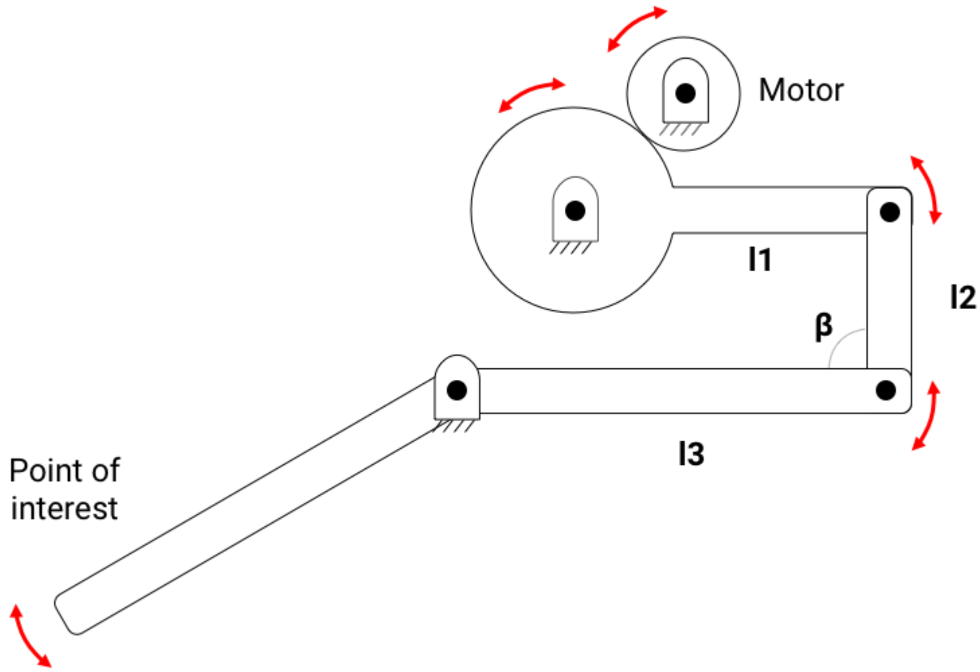


Fig.36: Kinematics diagram

4.3 Force Feedback Control

Humans perceive haptic feedback through mechanoreceptors in the frequency range from few Hertz to over 500 Hz, and the commonly applied computational frequency to run the force rendering algorithms is in between 500 Hz to 1kHz. We implemented the system with the ideal frequency to create a crisp contact. As stated in chapter 3.3.3, we developed four modes of force interaction: squeeze, custom, grasp, and click. The position of an index finger is measured by the flex sensor, which then computes the percentage of force that corresponds to one of the relationships in Fig.37 and generates output torque by setting it to the duty cycle of pulse-width modulation. An ideal force feedback is to explicitly control torque using current drive based on the required amount of force on the fingertip and making kinematics calculation to find the torque value employed to the motor pulley, but since the perfect replicate of the amount of force is not critical in this research, we decided to implement it in a simpler and a more stable approach. Moreover, force feedback is tuned at the initial contact to prevent wobbling and discomfort. This especially applies to the modes other than squeeze because it feels unrealistic if a high feedback is suddenly applied. It encounters the maximum feedback shortly after the initial contact.

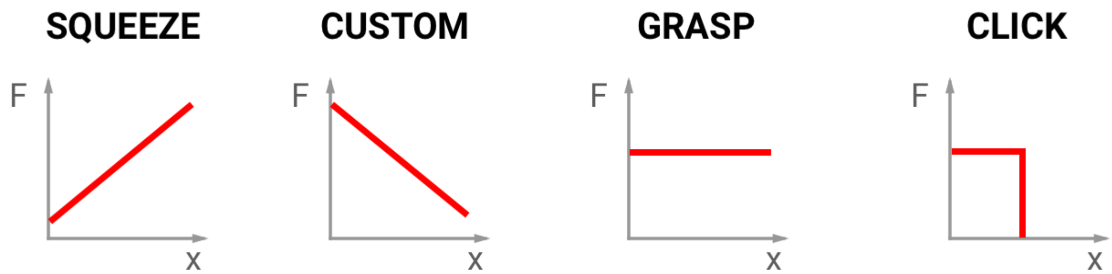


Fig.37: Force interaction patterns for 3D painting

4.4 3D CG and UI for 3D Painting App

The system takes input from the haptic device and the external cameras to generate a 3D mesh in real-time. Visual expressiveness is a key element of painting, therefore we developed three types of strokes: standard cylindrical stroke, metaball stroke, and particles effect (Fig.38). The standard stroke is applied to the squeeze and custom mode which changes its thickness based on the amount of press. The grasp mode creates the constant thickness metaball stroke, and the particles effect gets triggered by the click mode. The user can choose color and force interaction mode using 3D GUI.

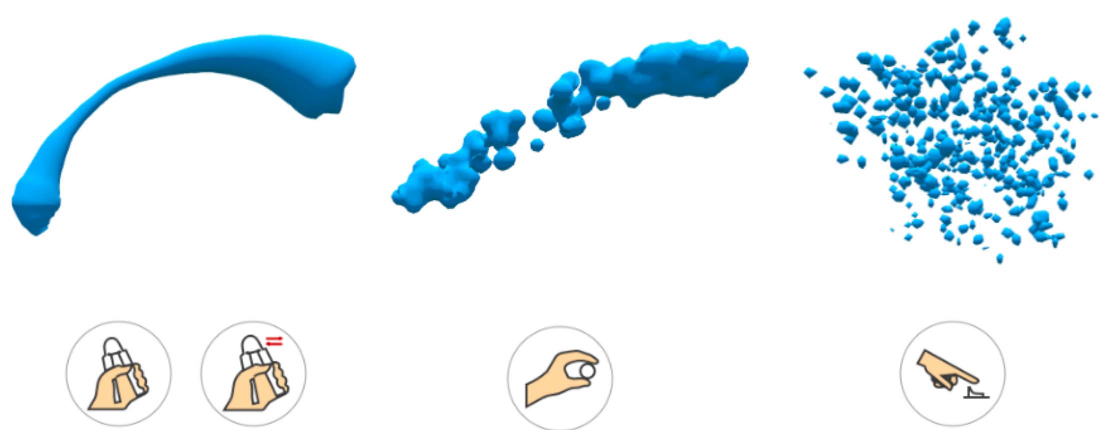


Fig.38: 3D stroke designs (standard, metaball, particles)

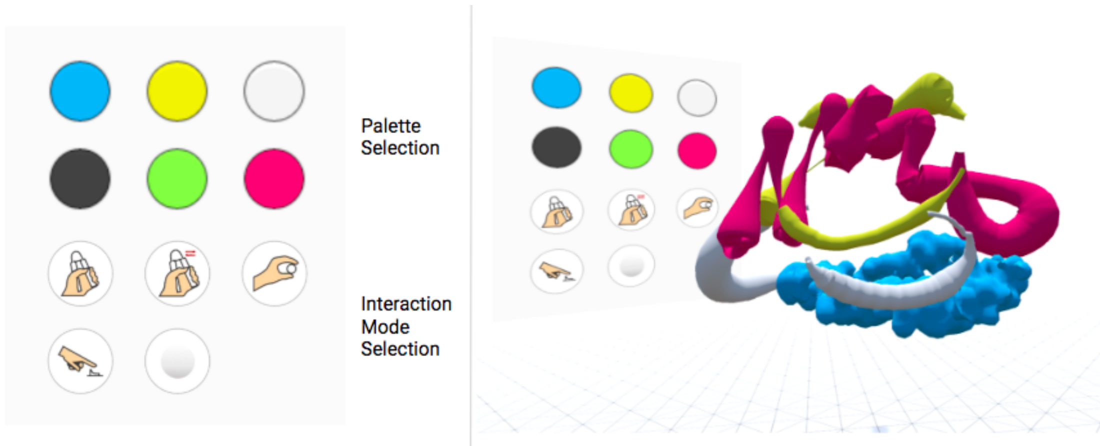


Fig.39: 3D GUI

4.5 Hardware-Software Integration

The final piece of the system is the display interface that enables direct manipulation of the 3D virtual environment in one-to-one scale. We selected HTC VIVE because this VR platform comes with external infrared cameras that enable stable absolute spatial tracking [63]. The 3D app is built to the VR platform which communicates with the haptic interface. An overall data flow is described in Fig.40.

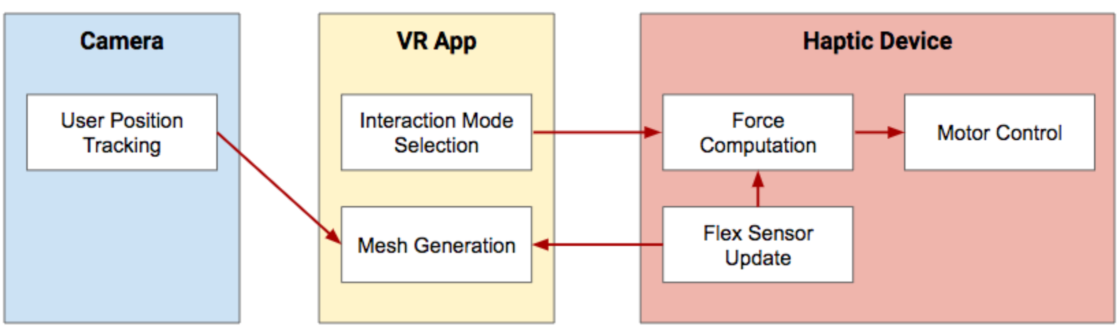


Fig.40: Diagram of the system data flow

Fig.41: Demonstration scene

5. Usability Evaluation

We conduct a case study format usability evaluation to determine the impact of force feedback haptics on 3D painting as explained in section 1.2. In this chapter, we describe the methodology of usability testing and the evaluation analysis of study results.

5.1 Methodology

We recruited a single participant whose background is in spray art to conduct in-depth studies, and we had additional single participant whose background is in pen drawing and digital design. Throughout three sessions of the study with the artist, not only we extracted insights from their feedbacks but also reflected them to the refinement of our prototype. We started with a contextual interview to understand how artists cope with haptic feedback of painting tools such as a spray can and brushes (section 3.3.2). We observed the artist working on his own artwork and asked questions intermittently. We spent roughly 30 minutes on the artwork and 30 minutes on an interview afterward. The second session aimed to introduce VR 3D application, to validate the usability of force interaction patterns, and to compare with non-haptics experience. We spent the first 20 minutes for demonstrations and the rest of time on an interview. The last session asked the participant to freely make a 3D artwork and gained feedbacks on using this system in the actual practice. After completing three sessions, we held a shorter study, which was equivalent to the second session, with another participant. We deliberately switched the order of demonstrating force interaction patterns to avoid getting biased data. The second and third sessions were both conducted in a lab setting.

	Contextual Interview	1st Usability Test	2nd Usability Test
Goal	To understand the techniques and affordance of painting tools	To compare the experience with non-haptic interaction	To evaluate the system in the process of making 3D artwork
Demo	Perform participant's own physical artwork	VR training and series of short demonstrations with and without haptic feedback	Perform 3D painting
Sample Interview Questions	-What is the criteria of choosing a tool? -How do you apply force when using a spray? When using a brush? -What defines a good/bad stroke?	-Did squeeze mode achieve fidelity of a spray can? -Was it intuitive to recognize the relationship between force and visual feedback? -How was the amount of force feedback? -How was the experience compared to no feedback?	-How did you utilize haptics for painting? Did it lead you to design different style of artwork? -Would you agree that force interaction improves the process of 3D painting? -Which mode of force interaction did you find useful while painting?

Fig.42: Process of case study

5.2 Hypothesis

This study focuses on evaluating force haptic interaction from two perspectives. The first perspective is the validation of the physical affordance fidelity and the second is the validation of metaphorical force interaction. In particular, we make the following hypothesis:

1. Sponge-like elastic force feedback driven by a hands-free device will improve the fidelity of spray painting compared to non-feedback interface.
2. Users will be able to intuitively map force feedback metaphors to the visual feedback of 3D strokes.

5.3 Result Analysis

Based on the observations and interviews with the participants, we drew five key insights related to force haptic interaction for 3D painting.

1. **A new category of tool**

   This tool is designed to be hands-free rather than handheld to maintain the full capability of hand dexterity, and we hypothesized that the elastic force feedback as a metaphor of pressing a spray nozzle will improve the fidelity of its physical affordance. However, both participants felt the interaction was unlike the real spray due to its large range of finger movement. We analyze that squeeze interaction was too generalized to be interpreted as a spray interaction. Physical affordance involves details of form, hardness, weight, and every other detail that the user feels, and its fidelity cannot be achieved without accommodating them. This is one reason that mimicry of physical interactivity can get complex quickly. An interface needs to perfectly replicate visual and force feedback or else the incorrect feedback can confuse the user rather than assisting their tasks. In this case with the squeeze mode, although it felt unlike spray, it functioned well as a metaphor and the participants were able to map force and visual feedback intuitively. One participant mentioned that the key attributes of a spray are nicely translated as a new tool. Therefore, we believe that defining its own affordance as a 3D painting tool is important rather than replication, and it should be communicated well with the user through both visual and force feedback.

2. **Force interaction is intuitive and easy to learn**
   There were four modes of force interaction (squeeze, custom, grasp, and click) that the participants experienced throughout the study and it was easy to learn the relationship between force and visual feedback. All modes of interaction could be distinguished without instructed. Furthermore, the amount of force feedback was strong enough to identify each interaction mode. It is especially important to note that the participant who joined three sessions of the study became familiar with force interaction by the third session (second usability study). He mentioned that force interaction was naturally part of his painting process.

3. **Preferences of interaction mode and affordance vary depending on participant's painting style**
   Two participants from this study had a different background in painting which led to perceiving the interaction modes differently. The participant with spray art and abstract painting experience loved using custom mode which generates a thick stroke initially with a large amount of force feedback because it felt similar to creating physical strokes. How the virtual stroke changed its thickness was also intuitive for him. On the other hand, another participant whose background is in precise pen drawings felt the custom mode was

confusing because he had never seen any interaction in both real and digital where the stroke transforms from thick to thin. Hence, force feedback felt unnatural as well. One possible assumption is that such gap between the two occurred due to the familiarity with different tools. Thick to thin effect can easily be accomplished using spray or thick brush, but not using pen tools. Other force interaction modes were similarly perceived by both participants, and both thought that the grasp mode was not useful because constant strokes can be achieved using squeeze or custom mode. There was another debate on hands-free versus handheld type device. One participant with spray background felt it was more convenient not needing to hold anything, whereas another participant felt unnatural for not having anything inside his palm.

4. **No-haptics mode makes it harder to accomplish ideal strokes**
   The experience of non-haptics mode was unpleasing for the participants. They needed to pay attention to visual feedback to get the right stroke and they were not able to make natural arm movements. One participant mentioned that being able to rest his finger on a single point of location helps greatly in making a consistent stroke.

5. **Enhances the capabilities of real-world painting**
   After conducting three sessions of in-depth study which involved refinement of the system prototype, the participant was able to create fluid painting strokes that he liked. In fact, he thought that he was able to master the skill in much shorter time compared to mastering physical paintings. It requires a lot of practice to get the ideal strokes on a physical canvas, but he could accomplish it on 3D canvas using the force interaction easily with the aid of computation.

6. Conclusion

This thesis demonstrates the design of force interaction techniques for room-scale 3D painting. We implemented a wearable force feedback device that takes metaphors of the real-world physical interactivity to explore its own affordance. In this concluding chapter, we discuss open-ended questions that arose from the usability evaluation, limitations of the current design, and future work.

6.1 Discussion on Affordance for 3D Painting

In this research, we aimed to create an apt tool for 3D painting that attempts to build its own affordance by using metaphorical force interaction. In particular, we designed one interaction that tries to achieve the fidelity of a spray can and another that is uniquely designed for this system. The first conclusion is that physical affordance cannot be achieved simply by translating a squeeze-like interactivity of a nozzle. We should acknowledge that the fidelity of affordance involves reflecting the correct amount of force feedback, range of motion, physical form design, and material property. Our interface was overly abstract that it did not capture many of the attributes of a spray. However, the second conclusion is that the metaphorical force interaction including the squeeze mode functioned well for the users and it should serve as a new tool that builds its own affordance for 3D painting. At the same time, the mastery of new affordance takes time and requires further explorations. Taking the physical form as an example, it is a completely different experience to use our hand as a tool rather than holding a physical tool, and there were contrary feedbacks related to the device comfortability. The spatial virtual experience itself is full of unknowns and we have not yet confirmed which device type works better. As one of the future works, further studies on force interaction and virtual affordance are necessary. In particular, comparing force interaction on hands-free and handheld types with a larger number of participants helps us understand which type of device feels more natural as a tool. Despite the challenges, we are excited to see new painting styles emerging from new tools. Similar to how every tool including spray can, brush, sponge, and pen leads to a different performative style of painting, a new set of virtual tangibility could lead to a style that has not been seen before.

6.2 Other Challenges

Force haptics combined with spatial UI is still in a nascent stage with regard to technical and experience design implications. One commonly raised issue related to VR is tethering and comfortability. Although VR is making a remarkable progress, tethering makes an overall experience limiting. While observing our participants creating 3D art, we could tell they were being cautious not to trip over the cables. The cables get in their way of freely working in the space. It is also challenging to remove cables from force feedback device because force feedback needs to be strong enough to be useful and it would require a large battery without cables. Again, the design engineering of electro-mechanics and interaction design becomes important to find a sweet spot.

Another challenge to be considered is the visual representation that fuses with force feedback. In general, humans identify an environment or an object through a visual cue and then perform appropriate tasks. Therefore, how the virtual environment, tool interface, and interactions are visually represented in our 3D application is critical to improving the quality of force interaction. As an example, currently the only visual feedback for confirming force interaction is the generated 3D stroke, but this could be improved by deforming a tool avatar (a simple sphere for the current version) as well. It would also be more engaging if there is a meter showing how much more needs to be pressed to trigger particle effect in the click mode. There is a lot of room for exploration in the visual representation of force interaction.

This is not directly related with haptics, but experiments on virtual environment affect the 3D painting experience. For instance, the methods to select palette and interaction mode were not fully tested. In this study, we selected to use a simple GUI, but similar to the previous attempt by Keefe et al. [7], the physical props for paint buckets could make the experience more engaging. Another experiment might be observing the digital paintings co-existing with the real-world environment using AR. It could produce unique aesthetics by incorporating the real wind, gravity, and time affecting the paintings.

Incorporating gestural interaction to the system is another interesting challenge for the future. The current system does not fully utilize the capabilities of finger gestures and it could add more interactivity for painting such as erasing strokes and changing menu options (e.g., color, interaction mode). However, the technical implementation of hand gesture tracking needs to be carefully considered. Adding another depth camera specifically for gesture tracking (e.g., Leap Motion) or adding sensors to the wearable device would, in either case, accumulates complexity.

6.3 Future Work

Application-specific digital tools such as a stylus overcome the problems related to affordance by replicating physical forms and functionalities as much as possible. One possible solution for 3D painting is also to use a brush or spray-like "prop" to mimic their physical affordance, but we chose to approach it differently. As described in Fig.43, the interfaces on the right-bottom utilize abstract metaphors that are suitable for generic applications, and stylus belongs to the left-top as a realistic metaphor for specialized applications. Conventionally, the interfaces have not been able to work across the spectrum simply due to their fixed physical form. We envision our tool to adapt to our hands naturally and to serve as a variety of specialized tool by maintaining its simple and generalized attributes. We hope to see the force interaction techniques that are conceptualized in this research to be implemented in other 3D UI applications as well.

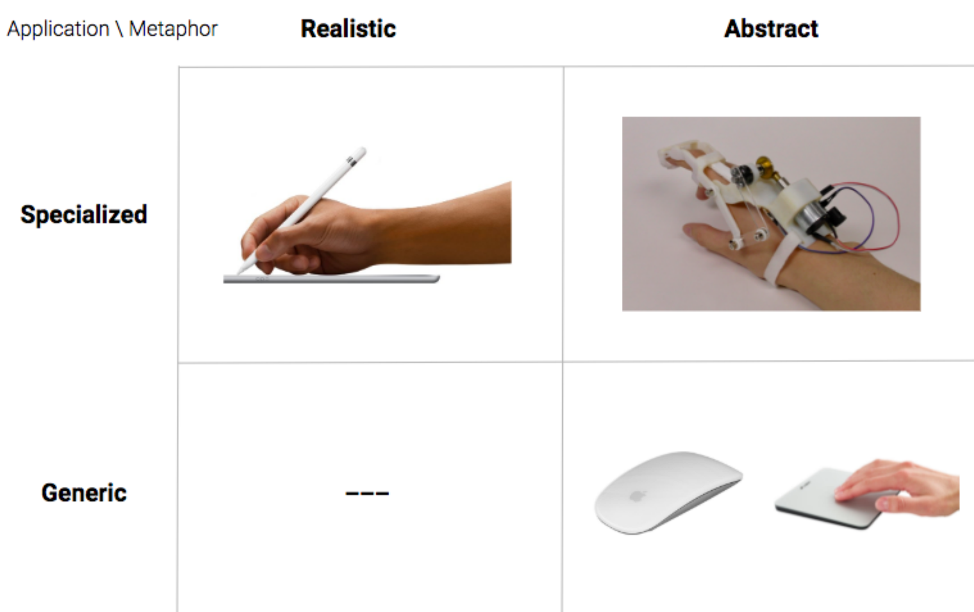


Fig.43: Ultimate vision of force interaction

Lastly, the adoption of 3D painting tool is essential in fostering its art culture. The value of painting is deeply rooted in the relationship between humans and tools that without the meaning behind the mastery of tools and its relationships with the culture, 3D painting is incomplete. Taking Andy Warhol as an example, his adoption of silkscreen printing upon mass production, celebrity portrait, and advertisement led to pop art movement. Silkscreen printing was the perfect choice for that time in reproducing iconic graphics efficiently, and such unique combination popularized silkscreen printing as an artistic technique. 3D painting has already been building its own culture primarily based on a computing and internet. Connectivity, openness, scalability, and human extension/augmentation are few features that are entailed. In a way, it is already a new form of art, but we believe it is incomplete and lacking the definition of its tool. The tool should resonate with the culture at the intersection of digital to analog, 3D to 2D, and intangible to tangible.

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