Hand-Mounted Tactile Displays for Haptically Identifying Shape and Dexterous Manipulation

Summary: Force-feedback, or haptic, applications in medicine, engineering, and design are increasing in popularity and importance based on the advantages of haptic devices in providing intuitive and realistic interactions with virtual environments. However, the use of current commercial haptic devices has been compared to interacting with the world using a stick, so the experience these devices provide fall far short of touch sensations encountered in the real world. In particular, current haptic devices lack integrated tactile feedback, which communicates contact and sliding between fingertips and an object. Although a variety of tactile displays have been developed, most are large bench-top devices and are impractical to place at a user’s fingertips while exploring a virtual object. Simpler, more compact devices will solve this problem and provide a means to create a more compelling virtual touch experience. The hypothesis of this research is that the addition of a simple tactile display to a standard haptic interface can greatly enhance the dexterous capabilities of these interfaces, and thus, the types of tasks and quality of work that can be accomplished in immersive environments.

The overarching objective of this research is to significantly improve the quality of touch feedback obtained with haptic interfaces by improving both the mechanical interface to virtual worlds and the supporting computational methods that generate touch sensations. These advances will be informed by and validated through a progression of human subject experiments that will culminate in two application-based evaluations in the areas of medical bone palpation and virtual assembly. These case studies will quantify the improved dexterous manipulation and exploration capabilities resulting from this research.

To accomplish these objectives, the PI has formed an interdisciplinary team with the project’s Co-PI and Senior Research Associate to create a series of new hand-mounted tactile displays and the new haptic rendering algorithms required to support the combination of these tactile displays and force feedback devices. To maintain the required small package size, these devices will only provide a limited set of tactile feedback (e.g., making/breaking of contact and the current location of contact), which has been shown to be effective in the PI’s prior studies. A primary focus of this study will be on the use of our developed system for shape perception and improved dexterous manipulation capabilities. This work will be guided by psychophysical experiments to understand relevant human perceptual limits in parallel with initial algorithm and device development to ensure a good fit between the device, algorithms and the human user. For example, prior literature has addressed the lack of smoothness when using faceted virtual models through the use of “force shading.” Similar phenomena will exist when adapting these models to also display contact location. Initial perception studies will both improve our understanding of how humans haptically perceive shape and provide design guidelines for our system.

Intellectual Merits: Building on the research team’s combined expertise, this award will help develop: (1) a new paradigm for haptics with tactile feedback for general 3D interaction with virtual environments by coupling tactile displays, developed herein, with commercial force-feedback devices; (2) enhanced performance and fusion of multiple types of tactile feedback in a hand-mounted tactile display; (3) improved understanding of how humans perceive shape with their hands; (4) new psychophysical performance guidelines for displaying contact location using general haptic models; (5) new algorithms for anticipating and rendering contacts for combined haptic and tactile display, with broader applications in robotics, simulation, graphics, and modeling; (6) a new medical training application; and (7) an advanced virtual prototyping application. This work will be potentially transformative in the areas of medical training and virtual prototyping by permitting a more intuitive interaction in virtual environments, allowing users to interact as though they were touching real objects with their bare fingers and capitalizing on their innate dexterous interaction capabilities.

Broader Impacts: This research will advance the state-of-the-art of haptic interactions, while also benefiting the medical and virtual assembly communities. The predictive geometric algorithms developed to support the tactile feedback are a novel fusing of robust constraint solving and probabilistic search, with further application for searching medical data, real-time robotics, and simulation, among others.

This cutting edge research with socially beneficial applications will appeal to potential women engineering graduate students. The researchers also plan to attract undergraduates by offering research sub-projects as capstone design, haptics course, psychophysics course, and VR course projects (classes the research team teaches). We will also aggressively recruit Native American and African American students from partnering Robotics IGERT institutions (of which the researchers are affiliated). This project also aims to leverage mentoring efforts with outreach activities established at both Utah and Purdue campuses by using these novel haptic devices to boost enthusiasm for engineering.

Key Words: Tactile Feedback, Haptic Rendering Algorithms, Shape Perception, Psychophysics, Haptics
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1 Introduction

Human interfaces for immersive virtual environments are often restrictive and frustrating, thereby limiting human performance and capabilities. These types of computer environments are increasingly important, for example in medical training, yet they have not fulfilled their potential as a truly natural human-computer interface. While high quality computer graphics are now the norm, the importance of having good haptic and tactile feedback is under-appreciated. Since what is experienced in the real world is a result of the seamless integration of visual, kinesthetic, and tactile information, without computer-generated tactile and haptic feedback, the ability to dexterously manipulate objects or even recognize shape is much reduced.

The objective of this research, then, is to improve the state-of-the-art of haptics by augmenting conventional force feedback devices with hand-mountable tactile displays. In particular, this research is focused on developing new tactile interfaces that will allow users in virtual environments to recognize and manipulate shapes and shape primitives via touch. In the context of this research, shape primitives are considered to be geometric landmarks on objects, such as ridges and high-curvature regions, that help users distinguish common objects. In contrast to prior research that has focused on the perception of objects of constant curvature (e.g., [92, 68, 121, 24, 34]), we are interested in developing devices and algorithms that permit users to mentally map these geometric landmarks during haptic exploration and to integrate these features into a global understanding of object shape. Object manipulation also depends on shape recognition to determine the current pose of the object being manipulated. Since kinesthetic force feedback is poorly suited to this type of shape recognition, the addition of tactile feedback is critical to the development of high-quality immersive interfaces that permit dexterous manipulation of virtual objects [28].

Our approach of adding a hand-mountable tactile display to a commercial haptic device is both supported by our intuition and also by several recent studies by haptics researchers. Frisoli et al. have recently conducted multi-finger virtual shape recognition experiments using point-force haptic feedback (i.e., force feedback without tactile feedback) with one, two, or three fingers [33]. Interestingly, the performance of subjects in these experiments did not improve with the use of multiple fingers. This is consistent with the findings of Jansson and Monaci, who conducted shape recognition experiments where subjects’ hands had splinted fingertips that explored physical objects [68]. Frisoli et al. attribute their observed reduction of performance to subjects losing contact with the explored object when using multiple fingers [33]. In a later paper, Frisoli et al. state that this loss of contact is due to the lack of rendered contact location, orientation, curvature and friction in typical interactions with point-force haptic devices [34]. In agreement with Frisoli, Jansson and Monaci have also suggested that adding more “spatially distributed” contact information to a haptic display is more valuable than adding multiple points of contact [68]. We are proposing to do both – that is, we will provide more tactile feedback on multiple fingers to support evaluation and manipulation of shape. This approach is further bolstered by recent work in haptically identifying common objects by touch. Lederman and Klatzky hypothesized that people may haptically build up object shape from primitives, using methods like contour following [92]. Though, when possible, the use of at least two fingers in haptic exploration permits enclosure of an object that provides an instantaneous “haptic glance” of an object, improving efficiency [92].

The hypothesis of this research is that the addition of a simple tactile display to a standard haptic interface will greatly improve the quality and utility of haptic interactions, both in the tasks that can be performed and the information that can be conveyed. This hypothesis will be tested within two important
application areas that are currently limited by the lack of tactile feedback – medical training and virtual assembly. These experiments are described briefly below and in more detail in Sect. 4.4.

The proposed team of multi-disciplinary researchers is well-equipped to tackle the challenges that this research will present. The team comprises researchers with experience in developing tactile displays, in creating haptic rendering algorithms, and in evaluating haptic devices via perceptual experimentation. Focused efforts will be concentrated in the areas of (1) design evolution of hand-mounted tactile displays, (2) haptic rendering for hand-mounted tactile displays, (3) understanding the perception of shape and object manipulation via contact location display, and (4) application-based evaluations of this research. The following subsections summarize some concrete goals in these four areas.

Project Focus Area 1: Design Evolution of Hand-Mounted Tactile Displays

The PI's prior research has focused on the development of a new class of hand-mounted 1-DOF contact location-based tactile display devices. In contrast to prior bench-top feedback devices, these tactile displays are worn on the hand, thus allowing more intuitive haptic interactions (Fig. 1). Using such a device, the PI has already shown that contact location can improve the perception of curvature and object motion [121, 119], and that displaying contact location is a successful strategy to maintain finger contact during contour following [91]. This device can also convey “enhanced” friction by applying skin stretch [142].

In support of this project's goals, the PI proposes a novel variable curvature contact element, schematically shown in Fig. 7. In addition to displaying various uniform curvatures, this deformable contact element would make it possible to create the sensation of asymmetrical contact, as would be experienced when contacting and sliding over the edge of an object (see Fig. 7(b)). Perfecting this design and measuring its benefits is one of the objectives of this proposal. The PI will also create a more general 2-DOF contact location display in the spirit of Fig. 2(b), which is more appropriate for general 3D environments. Hence, the results of this research will provide 3 of the 4 spatially distributed pieces of tactile feedback outlined by Frisoli et al. that are useful for shape recognition (i.e., friction, contact location, and curvature) [34].

The main elements of the required mechanical design research are: (a) modifying the current 1-DOF contact location display (CLD) to allow greater robustness and range of finger motion required for 3D environments. (b) Controlling fingerpad separation and contact between a person's finger and the device's contact element (which represents contact with the virtual environment). (c) Developing and refining the design of a variable curvature contact element. (d) Implementing a second degree of freedom on the CLD.

Project Focus Area 2: Haptic Rendering for Hand-Mounted Tactile Displays

Investigations to-date with these contact displays have been solely limited to validating their effectiveness in very simple haptic simulations. Therefore, despite the potential to interact in 3D virtual environments, the application of these devices has been confined to planar simulations.

We must improve algorithms to make the use of the proposed devices as accessible to general users as plugging in a Phantom haptic device. From a geometric standpoint, rendering contact forces for wearable tactile displays requires several novel properties. (a) The increased sensitivity of a tactile display is useless if the geometric representation and contact computation add spurious force discontinuities. Such tactile noise can easily overwhelm sensations, such as sharp edge detection, that motivate the use of a wearable tactile display. Modifying polygonal models or using spline models will be investigated. (b) Due to mechanical response limitations, contacts between the environment and the model of the finger must be anticipated before contact occurs, yet current haptic rendering algorithms are primarily designed to react after a collision. In response to these shortcomings, we will pursue new directions in accelerated solution of symbolic constraints applied to haptic rendering of CAD-style models for predictive contact. Because prediction is necessarily uncertain, a new direction for this research is to combine the robustness of a symbolic solver with probabilistic representations to yield estimations of future contact.

Project Focus Area 3: Understanding Shape Perception and Object Manipulation via CLD

There are many unknowns about the details of interpreting shape via contact location feedback. These unknowns will be investigated by teaming with the project's co-PI collaborator, Dr. Hong Tan, at Purdue University. Dr. Tan is an expert in designing and conducting psychophysical experiments with haptic devices. She will conduct focused psychophysical evaluations to better understand how we interpret shape via contact location feedback. These evaluations will provide the glue that will bind together and inform the development of the proposed devices and algorithms. (a) The initial experiments will begin by deriving the necessary criteria for algorithms and devices so that smooth surfaces and edges are properly identified, and not confounded by artifacts of the model representation. These studies will also derive design require-
ments, such as the maximum polygon size to obtain smooth surfaces and required positioning resolution and minimum motion bandwidth of the tactile display. (b) Once we can properly represent shape primitives/features, it is then interesting to investigate how users will integrate these features to form a global interpretation of shape. For example, as one moves a fingertip over a cube's surface s/he will experience broad contact on his/her fingertip due to the flat surface. The center of this contact does not shift if finger orientation is kept fixed relative to the object's surface. When the finger reaches the cube's edge, both the area of contact (and hence pressure) and contact centroid begin to shift. With contact location display, it is only the shift in contact location that is rendered. While the PI has already shown that this is sufficient to portray the relative curvature of objects [121], it is not entirely clear whether surface primitives such as edges and vertices will also be properly interpreted. (c) Once these essential building blocks for perceiving shape are understood, other influences such as object motion and friction will be introduced and isolated. This will bring about a better understanding of the overall benefits of using CLD for haptic exploration and manipulation. This understanding will enable our case studies in surgical training and virtual assembly.

**Project Focus Area 4: Application-based Evaluations of this Research**

As a capstone to this project, the newly developed capabilities of our haptic system will be evaluated in application-based human subjects experiments. One application area will be virtual prototyping, where the assemblability of CAD models is tested using a simulated peg-in-hole experiment. The other application area is in medical training, where surgical decisions are made based on a doctor's ability to discern landmarks on a vertebra via haptic palpation. These experiments will use metrics such as task accuracy and completion time as quantitative measures of the improvement that this research will provide. Results from these experiments will demonstrate the applicability to a broader community of end users with applications in VR, medical training and surgery, engineering, and design. Each of these experiments is described in more detail in Sect. 4.4.

The merit and impact of this research will be improved tactile feedback for complex tasks in 3D interaction and new interaction devices with the potential for broad impacts in human-computer interaction. Additionally, the new high-speed computational approaches developed in support of this tactile feedback provide a model for fast, robust computations in diverse areas such as robotics, medical simulation, animation, and geometric modeling. Psychophysical experiments will provide further insight into how humans perceive shape. The virtual palpation and assembly tasks will validate this research, showing the potential to directly benefit both the medical field and other important American industries.

The following sections provide a brief background and prior work of the research team related to tactile displays and haptic rendering algorithms. This is followed by the proposed research, intellectual merit and broader impacts of this work. The proposal concludes with results from prior NSF support and the project's collaboration plan.

### 2 Background

The inclusion of touch feedback into computer interfaces grew out of early work in teleoperation of robotic devices, which provided the mechanical devices necessary to instead experiment with manipulating computer models. Since then, haptic interfaces have become pervasive enough that they are even available in video game controllers, but the fidelity of interaction for even high-end devices is still primitive.

#### 2.1 Tactile Displays

Many examples of tactile displays have appeared in the literature. Quite often, these systems are also augmented with vibrotactile feedback (e.g., [88]), but this mode of feedback does not present geometric surface information. For a review of designs and relevant issues, see [134, 133, 80, 12, 135, 143]. General design guidelines for tactile display have been reported in [29, 116, 109, 4]. An evaluation of various actuator technologies is presented in [83].

The following subsections provide a review of previous tactile display designs. The PI has organized a taxonomy of tactile displays with three broad areas that are applicable for this research: tactile arrays, tactile displays that render skin stretch and slip, and glove-, hand-, or finger-based tactile displays. The category of tactile arrays has been further broken into two sub-categories: displays with an array of vertically-moving pins and displays with laterally-moving elements. Electrotactile displays would constitute a fourth category, but will not be discussed here for brevity. See [81] for a review of electrotactile arrays.

**Vertically Moving Pin Arrays**

Some of the first tactile displays were adapted from braille machines. In fact, some of the early experiments were completed with such a device, the Optacon [94]. Most braille
machines are driven by piezoelectric actuators, which have very good bandwidth but lack the actuation amplitude required to render curved surfaces with a haptic display. The performance of piezoelectric tactile arrays can be enhanced by using bimorph (piezoelectric) actuators [141], but the pin displacements are still less than 50 μm. To address these limitations, researchers began experimenting with tactile arrays driven by SMA (shape memory alloy) [55, 54, 163, 89, 176, 62, 130], electromagnetic [30, 115, 82], RC servos [172, 173, 67], pneumatic [23, 14, 110], electrorheological [105, 163, 171], and MEMS actuators [136].

Laterally Moving Pin Arrays  Another novel display design is presented by Hayward et al. [56, 93]. This device presents distributed skin stretch using an array of pins. It is particularly attractive because of its small relative size and ability to integrate with device electronics (e.g., [96]). This design applies skin shear at individual pins in the array and uses the procession of skin shear at neighboring pins to convey a sense of tactile motion. More recently, Luk et al. have adapted Hayward’s design to integrate into a portable music device to provide menu browsing feedback [96]. Fritschi et al. also present a similar design that utilizes RC servos rather than piezo-actuators [35, 25]. Similar to the PI’s tactile display, this display can be integrated with a kinesthetic force feedback device [36].

Skin Stretch and Slip Display  There are several other kinds of interesting devices that do not fall into the above categories that have been created to render slip and sliding motion at the fingertips. Salada et al. conducted some of the first studies that explicitly investigated slip or sliding as an important parameter to convey in haptic simulations [127, 126, 125]. Since then, others have also developed slip displays [168, 175, 36] and integrated this with a kinesthetic force feedback device [175, 36]. A number of groups have also looked at modulating the friction at the tactile interface as a means of tactile feedback [177, 10]. Other interesting approaches to tactile/kinesthetic display include work on shape and curvature interpretation using “change of height” [57] and local surface tangent [24, 138].

Glove- or Hand-Based Tactile Displays  There are a number of researchers that have produced glove- or hand-based tactile displays. A nice example is Moy et al.’s compliant tactile display [110]. They designed a tactile display composed of an array of small air pockets that is held to the fingertip with an elastic element [110]. Caldwell’s group has probably been on of the most prolific in the area of glove-based tactile displays [13, 15, 14, 168, 129]. His group has produced gloves with thermal-mechanical feedback [15], a pneumatic tactile pin array with shear and thermal feedback [14], and more recently hand-mounted devices that provide slip and skin stretch display [168] and a miniature pin array for shape and texture display [129]. The last of these designs is most like the approach the PI has taken in the past. That is, this device places a small 4x4 pin array on the fingertip of the user, while packaging bulky actuators on the user’s wrist or forearm.

Hand-based tactile displays continue to receive attention. As a relatively sophistication adaptation of work by Dostmohamed and Hayward [24], Salazzi et al. present an interesting finger-based tilting plate tactile display that provides similar information as the PI’s tactile displays [138]. Scheibe et al. present a minimalist design of a novel thimble-based 3x1 SMA wire pin array for use in Volkswagen’s driving simulator [130]. Minamizawa et al. present a band-driven fingertip contact and shear tactile display [102, 103].

2.2 Algorithms for Haptic Rendering

While algorithms for haptic rendering have developed along with broader advances for computing collision within the simulation and animation communities, haptics has its own distinct set of requirements. For example, collision updates at 60 Hz are generally considered adequate for visual rendering, yet haptic forces must typically be updated at 1000 Hz to maintain stability while rendering “hard” contacts [1]. However, in contrast to visual systems, haptic computations are generally proximal to a user-controlled model, so various efficiencies are possible by focusing resources locally around the contact locations.

The basic model for haptic rendering is to generate forces based on the amount of penetration between a model of the user and the modeled environment. In this case, the further the user model is pushed into the environment, the harder the haptic device attempts to push back. Computation of this penetration depth between two general models is still considered a fairly difficult task and is often approximated.

2.2.1 Point-Model Haptic Rendering

The earliest haptic rendering methods approximated the user as a point, reducing the computational burden to that of finding the distance between a point and a model. The very earliest methods embedded a vector force field within the environment to directly generate forces [66]. This approach proved unsatisfactory as it allowed the user to push through thin models and the vector field computation is difficult for all but the simplest of shapes. Another early approach decoupled the depth computation from the geometric
representation by computing an intermediate plane [1], based on the underlying model, that updated at a slower rate than the force computation. Forces were generated based on the distance from this plane. Thus, all computations were based on the boundary surface of the model, rather than an internal volume representation. The benefits of this boundary model approach were then fully realized in the “god-object” and “proxy” approaches [128, 124, 123], which constrained a point on the environment model surface to track the user-controlled point.

Concurrent work on haptic rendering of smooth, sculptured surfaces, represented as collections of NURBS patches, also used distance to the model boundary [165]. The main research issues for haptic rendering of sculptured surfaces are initializing the closest point on the model and stably updating the local closest point. A two-phase approach, a global anticipation phase and local update phase, is a useful model for maintaining high update rates [71].

2.2.2 Model-Model Haptic Rendering

By the end of the last decade, reasonable methods for haptic rendering of point interaction with general polygonal models, CAD-based sculptured models, implicits, and scalar fields were available. Research attention has since been focused towards allowing haptic interaction between two computer models. The primary complication is that while minimum distance suffices to measure the penetration between a point and a model, a new measure for penetration depth is needed in the general case, as the minimum distance goes to zero when two models are in collision.

Penetration depth is defined in terms of the vector between the solution points on the models being orthogonal to the respective tangent planes and thus, parallel to the surface normals at those points. Haptic rendering algorithms for general polygonal models have approximated the penetration depth by treating portions of the surface as convex patches, computing the minimum separation distance between patches, and merging these results into a penetration depth estimate [85]. In [76], this issue was avoided by computing all local minima between polygonal models and using these results as forces to push models away from contact. Sculptured models can use the penetration depth equations directly. In [113], an integrable rolling contact formulation was used for stable updates.

Another approach for generalized haptic rendering precomputes a hierarchical voxel model for the environment and a point sampling of a moving model [100]. The collection of forces between the points and voxels from obstacles defines the force and torque displayed by the haptic interface. More recently, the proxy approach has been generalized to the interactions between two polygonal models [101]. A proxy of one model is constrained to the other model's surface and forces are generated by an optimization routine that attempts to push the model back to its proxy. This has yielded high-precision rendering of haptic forces between two models, even allowing feeling individual facets of the models.

3 Prior Work

Our research team has extensive research experience in haptics. Outlined below is the PI's experience in tactile display development and associated perceptual experiments, and the Senior Research Associate's related experience in geometric computation for CAD and haptic applications, such as virtual prototyping, and the co-PI's prior experience in psychophysical evaluation of haptic interfaces.

3.1 Tactile Displays

The PI's prior research has focused on developing tactile display devices that can be worn on the hand and used in combination with commercial haptic devices. The addition of tactile information to these commercial haptic devices, such as SensAble Technology's Phantom [98], not only enhances the realism of the simulated environments rendered with these devices, but has also been shown by the PI to augment the perception of object curvature [119, 121], friction [142, 120], and relative motion during exploration [119, 91, 122, 121].

3.1.1 1-DOF Contact Location Display (CLD)

The PI first conceived of a new type of tactile feedback, referred to as Contact Location Feedback, during his dissertation research [119, 91, 121]. This approach represents virtual contacts by their centroid, like a ball bearing rolled over the surface of the fingerpad as portrayed in Fig. 2(a). To explore this concept, the PI has developed a 1 degree-of-freedom (1-DOF) device for portraying contacts along the length of the finger, analogous to moving a roller along the length of the fingerpad (Fig. 2(b)). Figure 1(b) provides a view of the device attached to a Phantom force feedback device.
The CLD apparatus utilizes a contact element suspended beneath the user’s fingerpad to convey contact location. It has been found that most user’s generally begin to ignore that they are wearing a thimble and are able to solely concentrate on the stimulus provided to their fingerpad within minutes of donning the device. The display’s contact element is attached to a Phantom, as depicted in Fig. 1(b). This haptic device measures the position of the contact element and provides reaction forces, which push the suspended element into contact with the user’s finger (see Fig. 3(b)). Making and breaking contact in this manner yields a realistic sensation of touch as the contact element stimulates mechanoreceptors in the user’s fingertip [180, 139, 90].

3.1.2 The PI’s Other Tactile Displays
The PI has recently developed two new tactile displays. The first is a so-called rotational friction display (RFD) [120] that uses a small friction disk to simulate rotational friction and sliding at the fingertips and the roles these play in exploring and handling objects and tools (see device concept and prototype in Fig. 4(a)&(b)). This device also directly integrates with a robotic force feedback arm.

An initial set of perceptual experiments, which were conducted in conjunction with the project’s co-PI, Hong Tan, investigated the perceptual thresholds for rates of rotational slipping at the fingertips [120].

The PI’s most recent device is a portable shear display for communicating direction cues (see device concept and prototype in Fig. 4(b)&(c)). The device imparts sub-millimeter skin stretch to the user’s fingertip. Details and initial results of this work are presented in [46].

3.2 Algorithms for Haptic Rendering
The Senior Research Associate has extensive experience in the development of geometric computations, particularly in support of haptic rendering. Concurrently with others’ work on haptic rendering of polygonal models, he participated in the development of some of the earliest haptic rendering algorithms for spline models, one of the earliest model-model haptic rendering algorithms, and one of the earliest algorithms for polygonal model-model haptic rendering.

[165] showed that the constrained surface tracking proxy model was equivalent to finding the closest point on a parametric spline surface and then updating that closest point using local numerical methods. This approach was extended to model-model haptic rendering in [113], which recast the local distance problem into one of penetration depth and used an integrable rolling contact formulation for stable updates.

Because polygonal models have discontinuous surface normals along facets, penetration depth is not well defined. Haptic rendering algorithms for general polygonal models have instead approximated the

![Figure 2: Concept for Contact Location Display (CLD). The (a) 2-dimensional or (b) 1-dimensional center of contact is represented with a single tactile element.](image)

![Figure 3: (a) Free-space motion creates no contact with the tactile element. (b) Touching a virtual object yields contact.](image)

![Figure 4: Other tactile displays designed by the PI. Rotational Friction Display (a) concept and (b) in use. Shear Display for communicating direction (c) concept and (d) prototype.](image)
minimum translational distance between convex patches and merged these results into a penetration depth estimate. In [76], this issue was avoided by computing all local minima between polygonal models and using these results as forces pushing models away from contact. These local minima were found using geometric hierarchies that bounded the symbolic equation for penetration depth. This approach has extended to robust model-model haptic rendering of complex, polygonal models [71, 72].

Much of these haptic results derive from more general results in distance computations [73, 69, 75], the stability of numerical methods for updating distance [74, 72], and more general techniques to solve problems posed as mathematical constraints [70, 131]. These results, along with the PI’s prior geometric environment (described below), provide starting points and insights for the development of the proposed haptic rendering algorithms supportive of tactile feedback.

3.2.1 Combined Tactile and Haptic Rendering

Due to the rarity of tactile displays, less attention has been paid to the particular needs of combined force feedback and tactile display. In [91], a planar, convex configuration obstacle of arcs and line segments was updated based on finger angle and used to compute the penetration of a finger arc into the model. This environment was mostly designed for perceptual studies and not as a general purpose haptic rendering algorithm. However, it does provide general insights into the properties needed by an algorithm for haptic rendering that includes tactile or contact location feedback.

For example, tactile feedback provides high frequency information, so faceted model representations generally introduce too many spurious high frequency transitions to be used with tactile feedback. Additionally, contact location feedback requires mechanical prepositioning of the contact element, and such prepositioning needs algorithms anticipatory of potential collisions. These are some of the geometric research issues that will be addressed in this proposal.

3.3 Psychophysical Evaluation of Haptic Interfaces

Hong Tan is best known for her work on haptic psychophysics. *Psychophysics* involves the quantitative modeling of the relation between a physical stimulus and a human response. Hong is interested in all aspects of touch as it relates to human-machine interface design and evaluation. She has often been credited for the methodology she has developed that brings to bear both engineering and psychophysical principles. Her work can be broadly categorized in three directions:

**Basic study of human perception of mechanical properties**, which provides basic human resolution data on force magnitude and direction, stiffness/compliance, vibrotactile amplitude/frequency/masking, and joint angle position (see [114, 148, 159, 21, 147, 7, 161, 65]). *This data helps interface designers select hardware and software parameters that match human sensory-motor capabilities.* For example, [161] describes how a study of joint-angle position resolution answers the question of fingertip resolution in free space. [21] provides evidence of human users servoing on constant penetration force while exploring virtual haptic terrains.

**Interface development and evaluation**, which includes the widely-known sensingChair, a tactor-array back display, a multi-finger interface developed for individuals with hearing impairments, a haptic texture rendering system, and an acupuncture training system (see [7, 158, 26, 149, 156, 151, 160, 155, 18, 17, 19, 22, 146, 183]). *These studies demonstrate combined engineering and psychophysical approaches to interface design.* For example, [151] uses information theory to evaluate human performance with a haptic interface. [17] provides evidence in engineering measurements to explain the phenomenon of perceived instability of virtual textures.

**Multisensory perception and crossmodal interaction**, which investigates crossmodal interactions such as haptic cueing of visual spatial attention, and compares human performance through the visual, auditory and haptic channels (see [7, 150, 50, 58, 40, 37, 59, 39, 42, 43, 6, 41, 38, 78, 44, 5, 48]). *The results have important implications for practical multimodal interfaces such as collision warning systems.*

3.4 Virtual Prototyping

The assembly task planned for research validation is an example of virtual prototyping. Utah haptics research has used virtual prototyping as a driving example [60]. Some examples are the introduction of haptic rendering of CAD models [164], interactive variational mechanical design [112], haptic manipulation of assemblies [111], and haptic rendering of accessibility tasks [77]. Most recently, the Senior Research Associate has published a study of force application in assembly tasks using full-arm haptics [32]. However, none of these examined the dexterous manipulation needed to correctly simulate the assembly of parts.
4 Research Tasks and Approach

As described previously, this research proposes to develop and refine a series of hand-mounted tactile displays, based on the PI's current designs, that can be used in combination with commercially available force feedback devices and used for general 3D interaction. To do this, the PI has formed an inter-disciplinary team to produce a series of new hand-mounted tactile displays, meant for use in 3D immersive applications, as well as new haptic rendering algorithms required to support the combination of these tactile displays with force feedback devices. As part of this, the PI will also produce a novel tactile contact element that is capable of changing its curvature at the point of contact. This allows us to more faithfully represent the local curvature of a virtual object. Human subject experiments will be used to investigate the perception of shape via contact location display (CLD) (see Sect. 4.3) and will also be used to assess the benefits of this research through two application case studies (see Sect. 4.4). Details concerning the device and computational developments are provided below.

4.1 Design Evolution of Hand-Mounted Tactile Displays

To make the stated goals more systematically achievable, the mechanical developments have been broken down into focused building blocks, which are described in the following subsections.

4.1.1 Active Control of Making and Breaking Contact

In prior work, the CLD had always been used such that gravity always forced the contact element away from the fingerpad (see Fig. 3(a)) allowing the Phantom to push the contact element up into the finger to initiate contact. As discussed previously, this feature is desirable as it enhances the realism of virtual contact. However, if a user were to invert their finger as shown in Fig. 5, the springs of the contact element would sag and create false contacts with the fingerpad. The PI believes it is critical to retain the ability to provide meaningful contact cues in expanding the device's use to 3D environments. To do this will require a sensor to measure the current separation between the contact element and the user's fingerpad and the development of a controller to maintain the gap between the fingerpad and tactile element using force provided by the Phantom. Initial steps in this direction have been completed using an IR optical emitter-detector to measure finger separation and the same thimble interface and spring coupling to the Phantom as the CLD (see Fig. 6 [47]). This simplified thimble-spring interface provides the same basic compliance and dynamics, and will permit sensor and control concepts to be developed in parallel with other work.

In the future, a controller to take advantage of this new sensor data will be designed. The controller is envisioned to provide both feed-forward gravity compensation and dynamic compensation, in addition to a closed-loop position controller for preventing false contacts. Once this controller is completed, this work can be applied directly to the current and future versions of contact location display.

4.1.2 Revised 1-DOF Contact Location Display (CLD)

To facilitate use of the 1-DOF Contact Location Display in 3D environments as well as provide more precise position control, the device design will be revised. The redesigned actuator will also include safeguards to prevent damage to the actuator in case the device should encounter controller instability during the course of the proposed work. The redesign will also seek to increase range of motion of the user's hand while

Figure 5: A thimble with cantilever springs attached to a contact block. Without a fingerpad sensor, the contact block will contact the fingerpad when inverted.

Figure 6: (a) Thimble interface with IR range sensor embedded in an epoxy contact block mounted to a robot arm. (b) Range sensor signal processing schematic as described in [47].
Figure 7: Variable curvature contact element. (a) The contact element can change radius of curvature from 1–50 mm. (b) By asymmetrically actuating the contact element it can represent leading or trailing edges.

wearing the device as well as to permit the devices to be used on the thumb and index finger simultaneously to permit multifinger virtual manipulation with tactile feedback.

This multifinger interface will permit us to investigate the effectiveness of contact location feedback for 2-fingered manipulation and exploration (e.g., in-hand exploration of curved objects). Building on the PI’s prior experiments [121], this 1-DOF display will be evaluated in the shape recognition and virtual assembly experiments (see Sects. 4.3.2 & 4.4.2).

### 4.1.3 Variable Curvature Contact Element

As part of this study, the PI will develop a novel variable curvature contact element for the 1-DOF contact location display, schematically shown in Fig. 7(a). This deformable contact element would also make it possible to create the sensation of assymetrical contact as would be experienced when contacting and sliding over the edge of an object (see Fig. 7(b)). This idea follows directly from the PI's prior investigations to “enhance” the perceived magnitude of friction by imparting skin stretch with the CLD. In this prior work, the PI utilized a wood block in place of the roller on his CLD for the purpose of imposing skin stretch. Prior to coating the wood block with rubber, the block readily slid over the user's fingerpad. This sliding occurred at relatively low levels of shear force that were hardly perceptible. Also, though the block was mildly curved (5 cm radius), when used in combination with graphics that suggested that a virtual surface was flat, a surface actually felt nearly flat. Taking note of this fact and the relatively low friction levels led to the idea of utilizing a thin, smooth sheet of shape memory allow (which allows several 100% strain to failure) over the top of a tightly radiused mandrel (see Fig. 7). The sheet will be preformed into a curved shape with a radius of approximately 5 cm and can be collapsed over a 1 mm radius mandrel. The ends of the sheet will be retracted in a manner similar to the tendon/band drives utilized in the finger mounted shear and contact display designed by [102, 103]. Perfecting this design and measuring its benefits will be one of the objectives of this study. To show the potential of this item, it will be evaluated in focused psychophysical experiments (see Sect. 4.3) as well as the bone palpation experiment (see Sect. 4.4.1).

### 4.1.4 2-DOF Contact Location Display (CLD)

One of the primary goals of this research is to create a 2-DOF contact location display that is able to display contact both along the length of the finger as well as across the fingerpad, as implied in Fig. 2(a). This will allow a user to roll objects between his/her fingers in any general orientation and experience the correct mapping and display of contact. Several design approaches are being considered, including an adaptation of the current 1-DOF design. This design concept will again use two push-pull wires, but in this case they would move independently rather than together, thus requiring an additional actuator. Near the thimble attachment, the connection between the push-pull wires and contact element would have a yoke design. This design would allow matched fore-aft motions of the wires to produce translation along the length of the finger, while differential motions of the wires would produce a lateral swinging motion of the contact element. This design could also utilize a piezoelectric ring motor in combination with a 1-DOF cable system rather than 2-DOF cable system. Another design under consideration is linkage-based and takes inspiration from a spherical 5-bar mechanism currently used in 2-DOF force feedback joystick designs [3]. In this design, the pivots would straddle the finger and the contact element replaces the joystick. Because of the complexity
of the device design, we propose to produce device prototypes in three stages, one each in years 2–4. The final design will be evaluated via human subjects testing (see Sect. 4.4.1).

4.2 Haptic Rendering for Hand-Mounted Tactile Displays

No current haptic rendering approach is fully appropriate for integrating kinesthetic haptic feedback with tactile feedback. For example, [101] claims rendering accurate enough that “each...face can potentially be felt”. Since the facets are artifacts of the polygonalization, such sensations overwhelm valid tactile feedback. Another difficulty in using existing approaches is that the proposed contact element needs to be positioned prior to impact. Existing polygonal rendering methods are generally reactive – they do not generate information until models interpenetrate. Thus, the contact element would not be properly positioned to respond to initial contact. A related issue is that while the penetration depth may be continuous using these methods, the contact location is not. Smoothing can mask this issue for kinesthetic haptic displays, but a contact location display does not have a stable contact point to render.

All of these factors argue for the development of new haptic rendering algorithms for model representations appropriate to combined force and tactile feedback. Such research would provide an advance over current approaches, which are unable to haptically render complex model interactions without introducing spurious tactile sensations. In response to this need, there are two main algorithmic directions we will develop for this proposal: reduced-artifact haptic rendering of polygonal models, which are widely available, and predictive haptic rendering for trimmed-NURBS sculptured surfaces, which are a de facto standard in computer-aided design and manufacture.

4.2.1 Polygonal Models

Prior work in haptic rendering of two surfaces [113] has established key capabilities necessary to predict potential contacts. Contacts between two objects may be represented by pairs of points at the location of the tangential contact. If the models move apart, these point pairs update to represent a local minimum in distance. If the models push together, the point pairs represent the penetration depth and contact locations that the rendering algorithm must update.

General polygonal models can be decomposed into collections of convex polyhedra. While efficient methods exist for the minimum distance between two convex objects, only approximate penetration depths are readily available. The exact solution is known, it is the closest point on the Minkowski difference of the two models to the origin. However, the full computation of the Minkowski difference is not fast enough for haptic rendering. We propose to use spatial coherency of the two moving objects and some existing fast techniques for sampling the Minkowski difference to construct enough local structure to find the exact penetration depth. Such exact computations have widespread application beyond contact location feedback.

Polygonal models of curved shapes introduce artifacts into the rendering process, as they only approximate curvature with flat regions and sharp edges. In kinesthetic haptic rendering, force shading [106] is used to smooth the surface normals as the contact point passes over polygon boundaries. We will investigate which techniques, such as local curved patches, are also appropriate to smooth the contact location.

4.2.2 Sculptured Models

Sculptured models, such as NURBS, can directly seek exact contact locations and surface normals to use in contact location display. Typically, numerical methods are used to provide fast updates while global techniques find discontinuous changes in solutions. Figure 8 shows the interplay between global and local methods needed to track and respond to model collisions. The basic computational components are to:

![Diagram](image)

Figure 8: Combinations of global search and local tracking are needed for haptic rendering. (a) A global search for local extrema initializes the tracking. (b) Local computations maintain haptic rate updates. (c) New global searches are needed to capture new extrema. (d) The local computations respond to transitions from collision anticipation to penetration depth and force computations.
1. Perform a global search for local minima in distance while two models are not in contact. Such minima represent estimates of potential, possible multiple, contacts (Figure 8(a) and (c)).

2. Update the local minima as the model moves. Such local updates are needed to keep the geometric computations updating at haptic rates, especially during transition events such as initial contact (Figure 8(b)).

3. Transition local minima in distance to penetration depth when the models make contact and local updates to the penetration depth as the models move (Figure 8(d)).

The combination of the global and local updates provides robust, yet fast, haptic rendering of complex NURBS models. The addition of trims to the model representation, which piece multiple NURBS patches together in topologically interesting ways, yields environments of realistic models. Each of these key capabilities requires research into new algorithmic approaches. However, we will be building on some promising theoretical developments for robust NURBS model computations as a foundation for this work.

4.2.3 Global Search for Local Minima in Distance

The global search is responsible for finding initial local minima point pairs and for adding new pairs as they are created. The minimum distance between NURBS surfaces \( f(u, v) \) and \( g(s, t) \) may be found at simultaneous zeros of the partials of the distance squared between the two surfaces. These partials represent the orthogonal projection of each solution point onto the other surface and can be written in simplified form as:

\[
\begin{bmatrix}
(f - g) \cdot f_u, (f - g) \cdot f_v, (f - g) \cdot g_s, (f - g) \cdot g_t
\end{bmatrix}^T = [0, 0, 0, 0]^T \tag{1}
\]

Recent developments for point-curve minimum distance using hierarchical hybrid numeric-symbolic spline solvers [131] show promise for robust solution of all local extrema. These solvers represent the constraint equations as splines using symbolic operations as splines, then use hierarchical bounds to identify potential solutions and numerical improvement to find exact solutions [27]. However, even the simpler case of minimum distance between a point and a curve, which yields a single one-dimensional constraint equation, currently can be solved only a few hundred times per second. The research challenge in this phase is to quickly solve the more difficult problem of extrema in distance between two surfaces.

Trims NURBS models allow patches to be pieced together in complex ways. From an optimization point of view, trims transform the force computation problem from a difficult, but straightforward, optimization problem to a constrained optimization problem. We will take the approach of decoupling the local extrema tracking from the trim constraints. Such an approach is only possible because the global search phase returns all local extrema, not just a single solution.

We propose to utilize locality and temporal coherence to gain greatly increased computation speed. Locality is important because we are not interested in extrema that are so far away that contact cannot occur before the next global computation. With fast updates, such a distance is small.

Temporal coherence can be used to reduce the number of new solutions sought at each time step. Since the old solutions can be updated using fast local methods, once the hierarchical global system identifies that a single, isolated root exists in a region of the domain, then the locally-updated old solution can be used instead. Drawing upon prior work in temporally coherent hierarchy traversal [69] and partial, dynamic caching of bounding volume hierarchies [75], we can amortize the cost of building the constraint equations over many temporal steps.

These results have the potential to broadly accelerate solution speed for a number of application areas that have already been solved using the symbolic solver approach, as well as provide a robust foundation for haptic rendering of NURBS models.

4.2.4 Higher-dimensional Formulations

While the above approach provides robust and fast haptic rendering of realistic CAD models, and provides some contact anticipation by finding local distance minima before contact, it does not use full trajectory information in its contact prediction. Such a limitation can be seen by a finger moving parallel to and above a tabletop. Even though the finger’s trajectory predicts collision with a wall, the current closest point predicts contact with the tabletop.

Our proposed approach is to represent symbolically future contact states of the finger model with the environment. This problem can be represented as a higher-dimensional state space directly as spline constraint equations. A solution manifold representing all possible contacts can be extracted as a preprocess and queried efficiently. The probabilistic notion of the trajectory can be encoded by sets of particles, each
representing a belief about a future state and potential contact. This new formulation gives more useful information to the tactile display for prepositioning the contact element.

4.3 Understanding Shape Perception and Object Manipulation via Contact Location Display

The perception and human performance experiments proposed here will be closely coupled with the development of the proposed displays and the haptic rendering algorithms with the goal to understand human perception of shape via CLD and guide and evaluate hardware and software development.

4.3.1 Basic Psychophysics for Informing Design Specifications

The perception and human performance experiments proposed here will be closely coupled with the development of the proposed displays and the haptic rendering algorithms with the goal to understand human perception of shape via CLD and guide and evaluate hardware and software development.

4.3.1 Basic Psychophysics for Informing Design Specifications

Initial experiments will serve to provide design specifications such as the maximum polygon size for rendering smooth surfaces and the positioning resolution for the contact location display. There are broadly speaking three basic types of psychophysical measurements: detection threshold (the minimum signal level of a stimulus that can be reliably detected by a human observer), discrimination threshold (the smallest difference between two stimuli that can be reliably detected), and information transfer (the number of correctly-identifiable stimuli within a range). There are well-established psychophysical methods for each type of the experiments [45]. In the context of our research, investigating a user’s ability to perceive a feature such as an edge or a nodule on an otherwise smooth surface can be done through a detection experiment. Understanding the relative merit of two representations (spline vs. polygonal) for rendering the same haptic model can be cast as a discrimination experiment. Gauging a user’s performance at recognizing a set of shape primitives requires an absolute identification paradigm. We will choose the most appropriate experiment design based on the research question being pursued.

One of the initial questions to be answered pertains to the guidelines for rendering fidelity with polygons and splines. While a spline-based representation is inherently smoother than a polygonal representation, it can also be more computationally expensive. Our question is therefore: At what resolution does a polygonal surface cease to feel smooth? Casted as a discrimination experiment, we can ask the equivalent question of when polygonal and spline surfaces feel different. The stimuli will be spherical surfaces rendered with polygons and splines. A 3-interval 1-up 3-down adaptive procedure will be used to estimate the smallest polygon size at which the polygon and spline models feel different (see [11, 7] for details on the experimental procedures). The independent variable is polygon size. Ten participants will be recruited, each completing six conditions (3 sphere radii × with or without smoothing for the polygon model). Based on our past experience, it takes 5-15 minutes to conduct each series. Therefore, we expect the whole experiment to last at most 1.5 hours per participant. The results will serve as initial performance criteria for the rendering algorithm. If, for example, we find that even with smoothing, a very fine polygon resolution is required such that it is more computationally expensive to use polygons than to use splines, then we will focus on developing spline-based models for our proposed research. The results will also quantify the trade-off between polygon size and smoothing.

Similar experiments will be conducted in order to achieve the following outcomes: 1) to derive some initial performance criteria for algorithms and compare criteria for rendering force vs. rendering contact location; 2) to derive some basic velocity, positioning accuracy, and bandwidth criteria for the mechanical device; 3) to investigate the influence of friction on the perception of shape; 4) to investigate the efficacy of using a variable curvature contact element for shape recognition; 5) to form further hypotheses as appropriate for additional experiments; and 6) to gain knowledge of whether it feels intuitive to feel an edge, a curve, and a flat surface at different object orientations. Interesting perceptual phenomenon, such as force shading [107], will be explored to improve computational efficiency without compromising perceptual fidelity.

4.3.2 Global Shape Perception from Local Shape Primitives

Once we are satisfied with the device and algorithm for representing local features, we will investigate how global shape perception is achieved by integrating shape primitives. These experiments will build on prior work by Frisoli et al. [33, 138] and Klatzky et al. [86, 87]. These authors have documented human’s remarkable ability at identifying common objects without vision with unconstrained fingers, and a marked decrease in performance with even simple geometries such as sphere or cube when only point-force kinesthetic information was available. The ability to maintain continuous contact with object contour was suggested as a key contributor to successful object identification (see also the PI’s prior work [91]). We expect that our CLD will provide the subtle cues indicating curvature changes including edges on an object.

Our shape recognition experiments will therefore utilize the PI’s CLD in combination with a Phantom force feedback device. The experiment design will parallel that used by Frisoli et al. [33] and will compare the
metrics of speed and accuracy of object identification both with and without contact location feedback, with 1 and 2 fingers. Initial pilot studies will be conducted to select approximately 15-20 object shapes making sure that they vary along several attributes such as size, number of vertices and edges and level of difficulty (to avoid the so-called “ceiling effect” in the sense that if performance without the CLD is high already, then it would be difficult to find out if the CLD can improve the recognition rates further). Ten human research subjects will be recruited (balanced in gender and their prior experience with haptic devices). Each subject will be asked to explore objects 10 times each and select a matching shape from a closed list. The order of object presentation will be randomized for each subject to eliminate possible training effects. Depending on the time it takes the subjects to explore the objects haptically, the experiment will be broken up into several runs lasting approximately 30 min. each and a 5 min. break will be enforced between runs to minimize fatigue. Results will be analyzed by ANOVA and paired t-test. These experiments will quantify the relative benefits of providing contact location feedback using the devices described in Sects. 4.1.2 and 4.1.4.

The results of these experiments will be further analyzed by building a stimulus-response confusion matrix to examine in details the confusion patterns between pairs of objects. This will help us gain insight into why some objects are confused more often than others. Our hardware and software system will then be reiterated to address the shortcomings discovered in this step of our research.

4.4 Application-based Evaluations

To quantify the benefits of this research, we will perform two human subject evaluations both with and without contact location feedback. These experiments will be focused on demonstrating: (1) the improved ability to recognize and integrate shape primitives into perceived global shape and (2) evaluate capability for dexterous manipulation and exploration for virtual assembly and prototyping applications with the CLD. These experiments will be performed with the 2-DOF Contact Location Display (Sect. 4.1.4) and multiple 1-DOF Contact Location Displays (Sect. 4.1.2), respectively. An overview of these experiments is provided below; however, the final implementation and details of each of these experiments will be determined through a series of pilot tests to ensure proper experiment design, analysis, and interpretation of results.

4.4.1 Bone Palpation Experiment

Our first application is motivated by an ongoing collaboration between the Purdue Co-PI Hong Tan and Dr. Brenda Austin who specializes in small animal surgery at Purdue’s Veterinary Clinical Sciences. In canine vertebrae surgery, parts of a diseased vertebra are removed with a drill to remove a disc extruding into the spinal canal. Before drilling, however, the location of the diseased vertebra as indicated by radiography, CT or fMRI needs to be mapped to the spine of the dog by counting its position from known anatomical landmarks. The surgeon accomplishes this by inserting one finger through an incision on the dog’s back to feel for the thoracolumbar disc region located between the last thoracic vertebrae and 1st lumbar vertebrae (see Fig. 9(a)). This disc space is identified by palpation of the last rib which angles toward the tail of the animal and the transverse process of the 1st lumbar vertebrae which angles towards the animal’s head (see also Fig. 9(b)). The surgeon can then count to the diseased vertebra previously identified by medical imaging and proceed to bone drilling.

For our experiment, the fMRI image of a dog’s spine (see Fig. 9(c)) will be used for visual and haptic rendering. One of the vertebra will be highlighted in color to indicate that it is diseased. The user’s task is to explore the vertebrae haptically until the diseased vertebra is located. An image of the spine will be shown...
on a computer screen (as it would be available to a surgeon), but unlike typical visuo-haptic rendering where the haptic interaction point is visually overlaid on the image, the position of the haptic device will not be shown to the user in our experiment. The location of the diseased vertebra will be randomized from trial to trial. The user’s task is to find the highlighted vertebra haptically as quickly as possible. The task completion time and errors (if the user identifies the wrong vertebra) will be recorded. Only non-medical students will be recruited for this initial evaluation. We will refine the simulation based on our findings. The results will directly benefit the ongoing veterinary surgical simulation project and will have important implications for similar haptic feature search and localization tasks in other medical simulation systems.

### 4.4.2 Virtual Assembly Experiment

A peg-in-hole assembly task provides a compelling, yet practical means to quantify the benefits of this research while at the same time bounding the complexity of task execution. It has been widely used in virtual and teleoperation assembly research ([95, 170, 132]; see also David Johnson’s prior work in virtual prototyping [60, 32]), robotic manipulation with force feedback [9, 63, 52], predictive bilateral control [108], shared control [53, 84], partial force feedback [169], tactile and auditory displays used in combination with force feedback [99], and the role of force bandwidth [61]. While prior studies provided only kinesthetic force feedback [52] and many used a stylus interface to represent a virtual wrench or screw driver that magically picks up a virtual object when the tool is sufficiently close by (e.g., [132]), our contact location display (CLD) allows a user to explore and manipulate virtual objects directly at the fingertips in a 3-dimensional space and therefore is expected to greatly enhance task performance.

Our experiment will utilize constant cross-section pins of varying shape (e.g., circle, hexagon) similar to shapes utilized in the experiments cited above. Pilot testing will be performed using a physical model and direct manipulation with unconstrained fingers (as in [86, 87]) to provide a baseline performance measure for later comparison with results collected in virtual environments. The pins will be approximately 50 mm in diameter (to avoid collision between tactile displays on the thumb and index finger). During the experiment using CLD and virtual objects, subjects will be presented with 1 pin and 2 holes of unknown shape and location and be required to identify, match, and place pin in the proper hole. This will require haptic exploration of both the pin and holes and then careful manipulation to properly place and orient each pin. As in the Shape Recognition Experiment (Sect. 4.3.2), each pin-hole combination will be repeated 10 times, in a random order, per subject. The variable curvature contact element will also be specifically investigated for its efficacy in such tasks. (Due to limited space, details of the experiment design are not repeated here.) Time intervals for critical stages of task completion (such as time to initial contact with hole and time to reorient pin before successful insertion) will be recorded to help understand the relevant contributions towards total completion time and results will be analyzed via ANOVA.

### 5 Intellectual Merit

Building on the research team’s combined expertise, this award will help develop: (1) a new paradigm for haptics with tactile feedback for general 3D interaction with virtual environments by coupling tactile displays, developed herein, with commercial force-feedback devices; (2) enhanced performance and fusion of multiple types of tactile feedback in a hand-mounted tactile display; (3) improved understanding of how humans perceive shape with their hands; (4) new psychophysical performance guidelines for displaying contact location using general haptic models; (5) new algorithms for rendering model-model interaction of exact, smooth models capable of anticipating and rendering contacts for combined haptic and tactile display, with broader applications in robotics, simulation, graphics, and modeling; (6) a new medical training application; and (7) an advanced virtual prototyping application. This work will be potentially transformative in the areas of medical training and virtual prototyping by permitting a more intuitive interaction in virtual environments, allowing users to interact as though they were touching real objects with their bare fingers and capitalizing on their innate dexterous interaction capabilities.

### 6 Broader Impacts

The proposed research will be closely integrated with educational activities at both Utah and Purdue. Specifically, sub-projects will be proposed as group projects in the following courses: Advanced Mechatronics and Capstone Design (Provancher), Virtual Reality (Johnson), and Psychophysics (Tan). The research team is experienced in teaching students from mechanical engineering, computer science, electrical and computer engineering, industrial engineering and psychology in their courses, as well as attracting undergraduate students to participate in their research laboratories.
The team has a strong track record in outreach activities that include mentoring robot competition clubs in local junior and senior high schools, running summer day camps for 8th and 9th graders with focus on 3D programming and robotics, demonstrating haptics technology to students from Historically Black Institutions, and running a 6th-grade nanotechnology science club at a local elementary school. To enhance the rigor of these outreach activities, we proposed to leverage an ongoing NSF/NUE project at Purdue to perform educational outcome assessment with the goal to move towards outcome-driven outreach activities. We have observed in the past how haptics technology can generate a “Wow” effect, and how its application in medicine and human-computer interaction can attract women students to engineering and computer science. Through rigorous educational research, we hope to firmly establish the “why and how” for contributing towards a more diverse student population.

In addition to broadly disseminating our research results to the scientific research community through conference presentations and journal publications, which the team has a strong track record of, we will also broadly share our findings from metrics-based outreach activities with our colleagues. The results from the proposed research and education activities are expected to contribute to many disciplines including robotics, medical simulation, design, animation, wearable computing, and assistive technology for individuals with vision or hearing impairments.

7 Prior NSF Support

W.R. Provancher, NSF-IGERT Grant DGE-0654414, $3,158,371, 9/1/07 - 8/31/12 (Co-PI, ongoing), “Interdisciplinary Research Training in Biocentric Robotics.” This Traineeship program emphasizes Bioinspiration, Bioinstrumentation, and Biomanipulation. It currently supports one of the PI's PhD students who has two conference publications [47, 46]. This proposal can leverage these new IGERT facilities and equipment.

W.R. Provancher, NSF-CAREER Grant IIS-0746914, $573,764, 5/1/08 - 4/31/13 (PI, ongoing), “CAREER: HCC: Haptic Guidance Systems.” The research theme is providing haptic guidance for such tasks as fine motor tasks and even navigation. This research explores the use of tactile feedback applied to fingertip to provide direction cues and the use of an active hand rest to provide improved support and corrective interventions. It supports two PhD students and has already resulted in one conference publication [46]. The PI is conducting haptics outreach to disadvantaged high school students in Utah’s Hi-Gear program.

H.Z. Tan, NSF Grant 9984991-IIS, $298,755, 4/1/00-3/1/04 (PI, completed), “CAREER: A Human-Centered Approach to Haptic Human-Machine Interface Research.” Results are summarized in [145, 137, 152, 157, 160, 182] (a sensing chair), [49, 50, 51, 144, 154, 155, 159, 166, 181] (a haptic back display imparting directional and attentional cueing), [16]–[20] (texture perception and rendering), [179, 178] (haptic perception of switches), [21, 174, 162] (data perceptualization), and [64] (a new haptic controller). L. Slivovsky and S. Choi received their PhDs in 2001 and 2003; S. Yang received his MS in 2004. One interdisciplinary course has been developed by H. Tan and Z. Pizlo (Dept. of Psychology, Purdue), and is now permanently cross-listed as “ECE511/PSY511 Psychophysics.” Tan has supervised 3 "vomit-comet" teams in the NASA Reduced Gravity Student Flight Opportunities Program in 1999, 2002 and 2004 [8].

H.Z. Tan, NSF Grant 0098443-IIS, $310,000, 8/1/01-7/31/04 (PI, completed), “Haptic Texture Perception and Rendering for Personal Robotics.” The goal of this project was to gain a deeper understanding of the perceptual dimensions associated with human texture perception. Results are published in [117, 118, 167] and [16]–[21]. Choi received his PhD in 2003; Leimgruber and Traylor received their MS in 2004 and 2005.

H.Z. Tan, NSF Grant 0328984-CCF, $285,134, 10/1/03-9/30/06 (Co-PI, completed), “Quantifying and Increasing Information Transmission with Data Perceptualization.” The goal was to quantify performance of scientific data perceptualization systems (visualization + haptic feedback) using information theory. Ross Maciejewski completed a Master's Thesis [97]. Tan's publications include [117, 118, 31] (haptic watermarking), [19, 20, 22] (texture rendering), and [161] (human finger joint-angle position resolution).

H.Z. Tan, NSF Grant 0533908-IIS, $481,052, 1/1/05-10/31/08 (Co-PI, ongoing), “Sensory Integration of Multimodal Human Computer Interfaces.” The main objectives are to identify the spatial and temporal parameters required for facilitatory multimodal interactions. Findings are presented in [153, 79, 48, 78, 140, 104], and two more journal manuscripts are in preparation.

8 Collaboration Plan

Major tasks and human resources assigned to these tasks are described below. Graduate students and their advisors are shown in Table 1, along with the investigators’ initials. Figure 10 provides a high-level view of the schedule, with a more detailed breakdown of tasks to be completed in each major area presented in the following sub-sections. Following each task are the investigators’ initials who are working on each task with lead investigators listed first. The project is mapped out by year and organized and listed separately by activities relating to hardware development (mechanical and electrical), simulation and haptic rendering algorithm development, perception experiments, and application-based evaluations. New hardware development and prototyping will be led by Dr. Provancher and his associated graduate students and will primarily take place at the University of Wisc...
Utah. Haptic algorithm development will be led by Dr. Johnson and his associated graduate student in Utah. Both Drs. Provancher and Johnson will support the development of controls related activities. Perception experiments will be led by Dr. Tan and her associated graduate student and will primarily be completed at Purdue with tactile display hardware and software supplied by Drs. Provancher and Johnson, respectively. Dr. Tan will be able to replicate Provancher’s current setup by utilizing her current Phantom Premium 1.0 by SensAble Technologies in combination with Provancher’s custom hardware. Dr. Tan will adapt Provancher’s and her own user interface experiment software to conduct human subject experiments and record data. Application experiments will be a group effort to integrate the knowledge gained by each researcher to provide a tangible demonstration of this research to the medical and design/VR communities.

A kickoff meeting will be held in the summer at the start of the project, which will provide an opportunity to focus the team and to become familiar with each other’s facilities. This meeting will include both PIs, the Senior Research Associate, and all graduate students working on this project. Travel budget has been allocated to allow for 1 trip for all participants to their collaborators’ lab in the first year. Thereafter, Purdue has been allocated slightly more travel budget since it requires less total resources for Dr. Tan and her student to visit Utah (2 vs. 5 travelers). Purdue has allocated more travel in year 4 in anticipation of more extensive travel to Utah’s campus to collaboratively conduct and complete our application experiments (see Sect. 4.4). This is also planned since the application experiments will need more hardware, which will only be available at Utah. This hardware will include the 2-fingered contact location displays (see Sect. 4.1.2) and 2-DOF contact location display (see Sect. 4.1.4), as well as the Phantom Premium 1.0 that Dr. Provancher has requested to be used with his existing Phantom Premium 1.0 for conducting our multi-fingered virtual assembly application case study (see Sect. 4.4.2). Travel for Utah participants to Purdue is also anticipated in order to observe experiments or to assist in hardware/software setup. The above travel budget is in addition to travel allocated for attending leading haptics conferences.

A project review and planning meeting is scheduled to occur annually at the start of the summer to disseminate and emphasize key findings from the prior year and focus the team for a highly productive summer. To help facilitate cross project communication, bi-monthly status meetings will also be held with all team members via skype or speakerphone teleconferences. These will primarily be used as a means to provide current progress and identify potential technical or schedule related issues. Significant communication between PIs and graduate researchers related to completing specific task areas is expected. Advisors or their students will be responsible for providing updates on activities (assigned below) in the bi-monthly status meetings.

8.1 Year 1 Plan

1. Hardware development activities
   (a) Refine fingerpad-to-contact element separation distance sensor to be compatible with a rolling cylinder or spherical contact element (WP)
   (b) Redesign contact location display (CLD) actuator to make it fail-safe and improve torque margin for greater rendering accuracy and speed (WP)
   (c) Examine and implement means to improve flexibility of actuator cable transmission and finger range of motion (WP)

2. Simulation and haptic rendering algorithm development
   (a) Implement a controller to enforce the separation between the fingerpad and contact element (WP & DJ)
   (b) Implement contact algorithms for simple convex polyhedra and single sculptured surfaces (DJ)
   (c) Develop contact location smoothing for polyhedral models (DJ)

3. Perception experiments
   (a) Design and conduct perception experiments with 1-DOF contact location display focusing on shape primitives (HT)

8.2 Year 2 Plan

1. Hardware development activities
   (a) Modify and manufacture a 2-finger version of 1-DOF contact location display (WP)
(b) Develop 1st prototype of 2-DOF contact location display (WP)
(c) Develop 1st prototype of variable curvature contact element (WP)

2. Simulation and haptic rendering algorithm development
   (a) Accelerate sculptured model rendering using spatial coherence and caching (DJ)

3. Perception experiments
   (a) Extract algorithm and device design guidelines from perception experiments (HT, DJ, WP)
   (b) Conduct perception experiments focusing on the influence of friction in interpreting shape and shape primitives (HT)
   (c) Perform perception experiments with combined object motion and shape cues (HT)

8.3 Year 3 Plan
1. Hardware development activities
   (a) Develop 2nd generation prototype of 2-DOF contact location display (WP)
   (b) Develop 2nd generation prototype of variable curvature contact element (WP)
2. Simulation and haptic rendering algorithm development
   (a) Develop contact location display for complex, trimmed CAD models (DJ)
   (b) Extend polygonal model rendering to arbitrary models (DJ)
3. Perception experiments
   (a) Conduct pilot tests for 3D shape perception with 1st or 2nd generation 2-DOF contact location display (HT & WP)
   (b) Perform perception experiments with variable curvature contact element that are focused on extracting shape and shape primitives (HT)
   (c) Conduct perception experiments for concave geometry for virtual prototyping application experiments (HT)

8.4 Year 4 Plan
1. Hardware development activities
   (a) Develop 3rd generation prototype of 2-DOF contact location display (CLD) (WP)
2. Simulation and haptic rendering algorithm development
   (a) Higher-dimensional space noisy trajectory prediction (DJ)
3. Perception experiments
   (a) Continue perception experiments for concave geometry for virtual prototyping application experiments (HT)
4. Application-based evaluations of this research
   (a) Bone palpation application experiment with 2-DOF contact location display (HT, WP, DJ)
   (b) Virtual prototyping application experiments with two 1-DOF or two 2-DOF contact location displays (HT, WP, DJ)
References


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