CHAPTER

Haptic Interfaces
Case Studies

This case study chapter will provide descriptions of several haptic devices, including the human factors specifications that influence the design, methods of implementations, and techniques for evaluating haptic devices. First, a desktop kinesthetic device will be presented as a case study of device evaluation via human-subject testing. Second, an exoskeleton device will be presented as a case study of human factors specifications and design implementation. Finally, the evaluation of a prototype tactile display, based primarily on hardware performance, will be discussed. These case studies do not comprise a complete picture of haptic interface design, implementation, and evaluation, but serve to present a basic representation of techniques and methodologies discussed in the book.

CS2.1 DESKTOP DEVICE EVALUATION

In this case study, O’Malley and Upperman (2006) were interested in humans’ ability to identify and discriminate shape primitives simulated with a haptic interface as compared to their performance of the same identification and discrimination tasks for real shape primitives. Shape primitives (in this case, square cross-section, and semicircular cross-section acrylic blocks) are defined as simple three-dimensional shapes that can be combined to form more complex three-dimensional objects. The study used basic human perceptual skills including identification and discrimination in high-fidelity virtual, low-fidelity virtual, and real environments. The researchers used a commercial haptic interface (PHANToM Desktop) to determine if results from prior work (O’Malley & Goldfarb, 2005) are generalized across hardware platforms.
CS2.1.1 Perceptual Environments

The real environment used for the perception tests incorporated round and square cross-section shape primitives fabricated from acrylic, placed on an aluminum base plate. A smooth-tipped aluminum stylus was fabricated to probe the shapes and had dimensions comparable to the stylus interface of the haptic device. Audio cues were masked by the sound of fans for the haptic device's motor amplifiers. The simulated environment, displayed via the PHANToM, was rendered to emulate the experimental setup. In order to test the real and simulated environments under what were considered similar circumstances, the real-environment interactions were constrained via a probe, rather than allowing the subjects to use a more natural configuration of the hand.

O'Malley and Upperman hypothesized that performance in the real environment would not greatly differ much from that in the high- or low-fidelity simulated environments rendered with the PHANToM Desktop, as was seen with the custom haptic device employed in O'Malley and Goldfarb (2005). Further, they hypothesized that force has less of an effect on performance than stiffness, since relatively low values of force were sufficient, whereas higher values of stiffness (relative to the achievable limit of the device) were necessary to reach the same level of performance. Finally, it was expected that simultaneously limiting force and virtual surface stiffness should not compound performance degradation, since limited force output does not significantly hamper performance.

CS2.1.2 Experimental Design and Procedures

Size identification and size discrimination experiments were performed in both real and simulated environments. For Experiments 1 and 2 (identification or discrimination), the within-subjects factors were the size difference between objects (1.25 mm, 2.5 mm, and 5 mm), the object shape (square and round), and the environment type (real, high-fidelity simulated, low-fidelity simulated [force], and low-fidelity simulated [stiffness]). For Experiment 3 (discrimination with varying force and stiffness), the within-subjects factors were the size difference between objects (2.5 mm, 5 mm, and 10 mm), the maximum output force (1 N, 2.2 N, 4.6 N, and 10 N), and the virtual surface stiffness (100 N/m, 220 N/m, 460 N/m, and 1000 N/m). A total of 10 subjects performed experiments in each of the simulated environments and in the real environment.

To vary the fidelity of the virtual environments, two machine parameters were selected to describe haptic interface machine performance, namely, maximum force output and virtual-surface stiffness. Force output correlates to torque output limits of motors, and increased torque output requirements are typically proportional to motor cost and size. When time delays are present in a system, the virtual-surface stiffness can be decreased to maintain stability. These two quantifiable machine parameters are easily understood by designers and are typical measures
of system quality. During experimentation, the maximum output force and the virtual surface stiffness were varied in the achievable range for the PHANToM Desktop device to mimic high- and low-fidelity virtual environments.

CS2.1.3 Experimental Protocol

For the size identification experiments, objects were placed, one at a time, in front of the subject. Each subject was asked to identify, via haptic interaction with the stylus-type probe, whether the object was the small, medium, or large object. For the size discrimination experiments, two objects of the same shape were placed side by side in front of each subject. Each subject was asked to determine, via haptic interaction with the stylus-type probe, which of the two objects was larger.

In all experiments, the subjects' view of their hand and the environments, both simulated and real, were shielded from view by a curtain. A single test session consisted of one size difference, one shape primitive, and one of the four environments. A training session prior to each test session was used to familiarize the subjects with the sizes of objects they would be classifying or discriminating, and provided the subjects with correct-answer feedback. Statistical power was ensured by using a sufficient number of subjects (10 per experiment) and trials.

CS2.1.4 Conclusions

Based on the experimental results, commercial haptic interface hardware such as the PHANToM may be capable of conveying significant perceptual information to the user at fairly low levels of stiffness and force feedback. While higher levels of stiffness force output in a haptic simulation may improve the simulation in terms of perceived realism, the results of these experiments indicate that high levels are not required to reach maximum performance for the size discrimination task in virtual environments. Additionally, human perceptual performance of virtual environments with the PHANToM Desktop haptic interface can approach that in real environments described here for the size discrimination task, but falls short for the size identification experiments. Results were in agreement with similar experiments conducted with a custom-designed haptic interface (O'Malley & Goldfarb, 2005).

CS2.2 EXOSKELETON DEVICE SPECIFICATION AND DESIGN

The second case study involved the design of a lower-arm exoskeleton intended for rehabilitation and training in virtual environments with force feedback. Many prior exoskeleton interfaces attempted to optimize one or more of the
following characteristics of the haptic system, namely, power-to-weight ratio (Lee et al., 1998; Tsagarakis et al., 1999; Jeong et al., 2001), workspace (Lee et al., 1998), wearability (Jeong et al., 2001) or stability, and control bandwidth (Rosenberg, 1993; Bergamasco et al., 1994; Nakai et al., 1998; Williams-II et al., 1998). Individual designs, however, achieve these optimizations at the expense of other useful features, usually workspace (Bergamasco et al., 1994; Nakai et al., 1998; Jeong et al., 2001) or control bandwidth (Lee et al., 1998; Tsagarakis et al., 1999; Jeong et al., 2001). Here, we present work that combines the useful results from prior research toward the design of a high-quality haptic interface with a workspace comparable to that of a human arm workspace. This is achieved at the expense of added weight and decreased mobility due to device grounding.

The MAHI exoskeleton, named for the Mechatronics and Haptic Interfaces Lab at Rice University, has been designed primarily for training and rehabilitation in virtual environments. These applications typically require the use of virtual force fields for guidance (Rosenberg, 1993) or active assistance (Gillespie et al., 1998; O’Malley & Gupta, 2003; O’Malley et al., 2006). The exoskeleton device must therefore allow natural human arm movements, with minimal reduction in workspace of the human arm. Because the device is to be worn, special care must be taken to ensure safety of the wearer.

Furthermore, mobility of the interface is not normally a requirement for such a system. Hence, the device can be grounded to support excessive weight, and gravity compensation can be implemented through the controller. Additionally, the low accelerations and velocities associated with human movements ensure that the inertia of the device plays a small role in its operation (Shimoga, 1992; Bergamasco et al., 1994). Therefore, when designing the MAHI exoskeleton, the kinematic design of the robot was given prime consideration. Table CS2.1 shows the desired design specifications for the exoskeleton in terms of the range of motion and torque display capability. The workspace specifications closely match the average range of motion of human joints. The torque capabilities lag far behind human abilities due to the limitations in the current actuator technology and some practical restrictions on the size of actuators that can be used in an arm exoskeleton.

The torques achieved by Tsagarakis et al. (1999) have been used as target specifications for design. Tsagarakis and colleagues employed pMAs with a tendon-based transmission for their exoskeleton design. This allows their exoskeleton to achieve high torque output and a larger workspace compared to prior arm exoskeleton systems. The disadvantage of using pneumatic actuation is the low bandwidth of the actuators and the requirement of delicate control due to their nonlinear behavior. Because the MAHI exoskeleton uses electric actuators, with lower power-to-volume and power-to-weight ratios than pneumatic actuators, the authors feel that the torque requirements of Tsagarakis and colleagues serve as a challenging benchmark.

Research has shown that fairly low stiffness and force values are sufficient for object detection (O’Malley & Goldfarb, 2002, 2004). Therefore, if a haptic
exoskeleton is designed for teaching arm movements using virtual force fields, a low-force output interface would suffice. In this case, as the authors intended for the device to be used as a general-purpose training tool for arm movements, it was required that the device be able to simulate high-quality virtual surfaces. As a result, emphasis was placed on the design of a high-performance interface, which encompasses the human arm workspace. In addition, for rehabilitation applications, the ability to control feedback to individual human arm joints is desirable and was addressed through this design.

**CS2.2.1 Basic Mechanism Design**

The basic kinematic structure of the 5-DOF MAHI exoskeleton comprised of a revolute joint at the elbow, a revolute joint for forearm rotation, and a three-revolute–prismatic-spherical (3-RPS) serial-in-parallel wrist, as shown in Figure CS2.1. The choice of a parallel mechanism for the design of the exoskeleton wrist

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**TABLE CS2.1** Workspace and Torque Output of MAHI Exoskeleton Compared to Human Capabilities

<table>
<thead>
<tr>
<th>Joint</th>
<th>Human Isometric Strength</th>
<th>Human Arm W/S</th>
<th>Peak Torque Output (Exoskeleton) W/S</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Elbow</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Flexion/extension</td>
<td>72.5 Nm</td>
<td>Flexion: 146 degrees Extension: 0 degrees</td>
<td>55 Nm 90 degrees</td>
</tr>
<tr>
<td>Supination/pronation</td>
<td>7.1 Nm</td>
<td>Supination: 86 degrees Pronation: 71 degrees</td>
<td>5.08 Nm 90 degrees</td>
</tr>
<tr>
<td><strong>Wrist</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Palmer/ dorsal flexion</td>
<td>19.8 Nm</td>
<td>Palmer flexion: 73 degrees Dorsiflexion: 71 degrees</td>
<td>5.3 Nm Palmar flexion: 42 degrees Dorsiflexion: 42 degrees</td>
</tr>
<tr>
<td>Adduction/ abduction</td>
<td>20.8 Nm</td>
<td>Adduction: 33 degrees Abduction: 19 degrees</td>
<td>5.6 Nm Adduction: &gt;33 degrees Abduction: &gt;19 degrees</td>
</tr>
</tbody>
</table>

*Source: From O’Malley and Gupta (2006).*

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over a serial mechanism was motivated primarily by the compactness of the parallel mechanism. Furthermore, use of a parallel mechanism allows for higher torque output, stiffness, and decreased inertia compared to a similar serial mechanism.

During operation, the robot is worn so that the axis elbow joint of the robot aligns with the operator's elbow joint, and the top plate of the wrist of the robot aligns with the wrist joint of the operator. This configuration aids in preserving natural arm movements by aligning the robot's kinematic structure with that of the human arm. Velcro strapping and an ergonomic palm splint are used to maintain this alignment. The mapping between the robot configuration and arm position is further simplified by the use of the 3-RPS kinematic structure for the robot. The wrist platform dimensions were determined via design optimization, with the goal that the height of the platform and the travel of the links are kept to a minimum, so that the base is as close to the human wrist as possible.

CS2.2.2 Sensing

Sensor resolution affects the range of frequencies of forces that can be displayed by the haptic interface (Colgate & Brown, 1994). Consider, for example, the simulation of a thin virtual wall. If the sensor resolution or the computational speed is not high enough, then there exists a possibility that the human can pass his/her arm through the wall without feeling the force. Furthermore, during simulation

![Kinematic structure of MAHI arm exoskeleton. Source: From Gupta and O'Malley (2006) and Sledd and O'Malley (2006); copyright © 2006 IEEE.](image)
of stiff virtual surfaces, reduction in sensor resolution increases the delay in sensing the human's actions in the virtual environment, and this delay can decrease system stability. With these considerations, high-resolution optical encoders were selected for the device.

CS2.2.3 Actuation

The actuators for a haptic device determine the range of magnitude and frequencies of forces that can be displayed with the interface. To reproduce real-life environments, it is desirable that the device be able to display forces in a large range of magnitudes as well as frequencies. In general, the use of high-power actuators is accompanied by an increase in weight, thereby increasing the inertia of the device. Thus, high power-to-weight ratio and high bandwidth are desirable qualities for actuators used in a haptic interface. The bandwidth refers to the dynamic response of the actuator; a low-bandwidth actuator fails to display high-frequency forces to the operator, reducing system transparency in such situations.

This gains importance in that human kinesthetic/proprionicceptive sensing bandwidth is 20 to 30 Hz and tactile sensing bandwidth is 0 to 400 Hz (Shimoga, 1992). No single actuator technology provides the benefit of both high power-to-weight ratio and high bandwidth. Pneumatic actuators are inexpensive and provide the benefit of high power-to-weight ratio. However, pneumatic actuators have a low bandwidth, which limits their utility as actuators for haptic interfaces. Tsagarakis and coworkers used pMAs for their exoskeleton (Tsagarakis et al., 1999). However, these actuators have highly nonlinear dynamics in addition to low bandwidth, making them unsuitable for application in haptic devices. Hence, electrical actuation was chosen for the MAHI exoskeleton. Electrical actuators have a lower power-to-weight ratio than pneumatic actuators, but have very high bandwidth. This increases the weight of the device but allows for better force reflection through the interface. The specific design goals and achieved quantities for the exoskeleton design are given in Table CS2.1.

CS2.2.4 Transmission and Actuator Placement

A transmission can be used to increase the torques or forces delivered by the device, but at the expense of speed of operation. The bandwidth of human motor output, which represents the ability of the hand and fingers to exert force, is 10 to 15 Hz (Shimoga, 1992), thus making the use of a transmission in haptic interfaces advantageous. Furthermore, use of a transmission allows the actuators themselves to be placed closer to the base of the robot, reducing rotational inertia. Use of transmissions, however, is associated with trade-offs like backlash, nonlinear dynamics, and complex cable routing. For example, gears introduce backlash into the system, whereas cable and belt drives introduce nonlinearities. For the MAHI
exoskeleton, cable transmissions were used to transform rotary motion of the wrist platform actuators into the translational motion of the overall wrist platform. For the elbow flexion/extension joint, a cable drive enables torque output of the joint to achieve desired values. For the forearm pronation/supination motion, frameless electrical actuators were selected to keep the increase in inertia to a minimum.

CS2.2.5 Other Design Considerations

To free the elbow actuator from the constant demand of supporting the weight of the forearm system against gravitational forces, a counterweight was incorporated for compensation. The counterweight is directly linked through a moment arm to the elbow motor shaft that supports the forearm assembly, ensuring accurate and continuous gravity compensation. To support the added weight on the elbow mounting shaft and to reduce friction, the shaft now rotates on two large ball bearings in parallel along the axis of rotation.

Although such a counterweight gravity compensation system introduces inertia into the system, once freed from the gravitational load of the forearm mechanism, the elbow actuator becomes capable of managing this increased inertia while providing better performance than if it was required to actively support the forearm at all times. In addition to gravity compensation, precision-manufactured components, rigid materials where called for, and an overall minimal number of components in the assembly were key to a design that limited friction and backlash in the overall assembly. The result is a mechanical system with smooth and rigid action.

The use of off-the-shelf components also reduced build time and cost of the new exoskeleton. Finally, materials selection was carefully considered. The device uses frameless electrical motors for the forearm joint and is made almost entirely of aluminum. Due to the use of frameless actuators, the amount of material required for construction was tremendously reduced. Aluminum was used for construction over lightweight polymers like carbon fiber for several reasons. First, aluminum has much higher stiffness than polymers. Second, polymers like carbon fiber are typically stronger under axial loading than transverse. Third, being metallic, aluminum components are conducive to the performance of frameless motors.

CS2.2.6 Safety and Comfort

During the design process, precedence was given to compactness of the design and robot kinematics. A direct drive mechanism was used to avoid backlash and nonlinearities associated with transmissions. As a result, the MAHI exoskeleton weighs more than 3 kg. Therefore, the device was grounded to the wall to reduce discomfort to the user. The workspace of the exoskeleton is greater than the workspace of the human arm for some joints (see Table CS2.1). In such circumstances,
hardware stops in conjunction with software limits have been used to ensure user safety. Emergency stop switches are also provided.

CS2.3 TACTILE DEVICE EVALUATION

Wagner and colleagues described a 6 x 6 tactile shape display design that is low in cost and easily constructed, using commercially available RC servomotors to actuate an array of mechanical pins (Wagner et al., 2004). The given specifications of the device follow: The pins deflect a maximum of 2 mm, with a resolution of 0.1 mm. The pin center spacing is 2 mm and the pin diameter is 1 mm. For the maximum deflection of 2 mm, the display can represent frequencies up to 7.5 Hz; smaller deflections lead to achievable frequencies up to 25 Hz because the servos are slew-rate limited. The prototype system is shown in Figure CS2.2.

The design specifications used by Wagner and coworkers are derived from those proposed by Moy et al. (2000) for array-style tactile displays. Such
specifications state that the tactile display should have a bandwidth of at least 50 Hz, an actuator density of 1 per square millimeter, and a maximum pressure of 50 N/cm². Additionally, Moy et al. (2000) state that each actuator should indent up to 4 mm with a height resolution of 10 percent. Other desirable features indicated by the team include small actuator size, high reliability, and low cost.

For this case study, the evaluation methodologies for the tactile display are presented, summarized from the initial publication of results in Wagner et al. (2004). The tactile device’s control system allows for 24 incremental position commands to be sent to a single servo (for a single pin) over a 2-mm height range. To characterize the height resolution of a single-pin assembly, the servo was given incremental position commands over three trials, the pin height was measured, and a linear relationship was found. The maximum error between pin height and a true linear trend between height and position command was determined, along with the standard deviation of the error, to determine the height resolution of the pin assembly (±0.1 mm).

To determine the transient characteristics of the display, a pin was commanded to track a sine wave and square wave with specified pin height amplitude. Actuator characteristics result in a limit in the slew rate, and delays between command and servo movement were also determined with this procedure. From these data, the maximum displayable frequency for the specified pin displacement height was determined.

Next, the force displacement characteristics of several pins were measured using a force sensor mounted to a vertical stage. The force displacement characteristics of the pin assembly can vary due to the stiffness of the pin wire and the active position control implementation of the servo. These measurements are influenced by the stiffness of the pin wire and the active position control of the servo. The team determined that due to the high stiffness of the pin wire with respect to the stiffness of the human finger, the display was suitable as a position display.

High-frequency noise (both auditory and tactile) in the tactile display was noted and attributed to the digital nature of the servo position controller and servo commands. Additionally, the servo gearing mechanism introduced high-frequency vibrations. Because auditory cues are often masked during psychophysical evaluation of the tactile devices, the focus of the evaluation was on the characteristics of the high-frequency tactile noise. To do so, an accelerometer was placed on top of a stabilization plate resting on all 36 pins of the tactile display. A bias weight provided a constant force to maintain contact between the pins and the plate. The pins were commanded to simultaneously track a vertical sine wave, and the magnitude of the vibrations versus frequency was measured and compared to the threshold for tactile perception (Verillo, 1966). The tactile vibrations were found to be small with respect to low-frequency motions. A final evaluation step was to compare the performance of the tactile display with other state-of-the-art solutions using other actuator and sensor technologies.
REFERENCES


