Evaluating Multimodal Feedback for Accomplishing Assembly Tasks in Virtual Environment

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ABSTRACT

Operating power tools over extended periods of time can pose significant risks to humans, due to the strong forces and vibrations they impart to the limbs. Telemanipulation systems can be employed to minimize these risks, but may impede effective task performance due to the reduced sensory cues they typically convey. To address this shortcoming, we explore the benefits of introducing simple vibrotactile cues, in addition to auditory and low-level force feedback, on users' performance in a VR mechanical assembly task employing a simulated impact wrench. The vibrotactile effects rendered in this study represent not only collision states, but also simplified and attenuated renderings of the vibrations experienced while operating an actual impact wrench. Results from a user study comparing feedback modality combinations suggest that the introduction of vibrotactile feedback, in addition to auditory feedback, has the potential to significantly improve user performance as assessed by completion time, while the addition of force feedback did not further improve performance.

RÉSUMÉ SCIENTIFIQUE

L'utilisation d'outils électriques pendant de longues périodes peut présenter des risques importants pour les humains, en raison des forces et des vibrations importantes qu'ils transmettent aux membres. Les systèmes de télémanipulation peuvent être utilisés pour minimiser ces risques mais peuvent entraver l'efficacité des tâches en raison des signaux sensoriels réduits qu'ils transmettent généralement. Pour combler cette lacune, nous explorons les avantages de l'introduction de signaux vibrotactiles simples, en plus de la rétroaction de force auditive et de bas niveau, sur la performance des utilisateurs dans une tâche d'assemblage mécanique VR utilisant une clé à chocs simulée. Les effets vibrotactiles rendus dans cette étude représentent non seulement des états de collision, mais aussi des rendus simplifiés et atténués des vibrations subies lors de l'utilisation d'une clé à chocs réelle. Les résultats d'une étude utilisateur comparant les combinaisons de modalité de rétroaction suggèrent que l'introduction de rétroaction vibrotactile, en plus de la rétroaction auditive, pourrait améliorer significativement les performances de l'utilisateur en fonction du temps d'achèvement, tandis que l'ajout de retour de force n'améliorerait pas les performances.

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[1] This is used to generate the superscript on the title.

List of Acronyms

AR	Augmented Reality
CAD	Computer-aided Design
CTS	Carpal Tunnel Syndrome
ERM	Eccentric Rotating Mass
FOV	Field of View
GPIO	General-Purpose Input/Output
HAVS	Hand-arm Vibration Syndrome
HCI	Human-computer Interaction
HMD	Head-mounted Display
HMI	Human-machine Interface
HRI	Human-robot Interface
HTV	Hand-transmitted Vibration
IMA	Industrial Maintenance and Assembly
LRA	Linear Resonant Actuator
MCU	Microcontroller Unit
MR	Mixed Reality
MSD	Muskuloskeletal Disorders
NPD	New Product Development
OSC	Open Sound Control
PWM	Pulse Width Modulation
ROS	Robot Operating System
TLX	Task load index
VR	Virtual Reality
VWF	Vibration White Finger
WBV	Whole-body Vibration
3D	Three dimensions

Chapter 1

Introduction

1.1 Thesis Outline

The large amount of energy that power tools can release makes them particularly dangerous. The heavy mass of power tools, and the strong forces and vibrations they impart to users, are common causes of nerve and musculoskeletal disorders (MSD), especially for inexperienced operators. Even among expert operators, prolonged use was shown to be the cause of serious physical ailments [1, 2, 3, 4]. Examples of these situations include instances when the operator needs to operate the power tool for a short period of time, repetitively, e.g., tightening lug nuts on car wheels, or for a long period of time e.g., making holes in the ground with earth auger, or a combination of the two. Other known issues such as white finger syndrome or hand-arm vibration syndrome (HAVS) were shown to be caused by continuous use of vibrating hand-held machinery. The onset of MSD and HAVS on patients' quality of life is multifaceted, negatively influencing their general health and physical functioning, and their emotional and social functioning indirectly [5].

To minimize the occurrence of industrial injuries in the workplace, systems were created to reduce the amount of mechanical energy transmitted from a power tool to its users. While simple solutions such as anti-vibration gloves are available on the market and offer some level of protection, they provide negligible attenuation of forces experienced by the operators. The primary motivation of this research originally stems from a demand to create an interface between human operators and power tools, in order to eliminate potential safety issues produced by operating power tools directly, as well as facilitating working progress. Under these circumstances, robot-mediated (telemanipulation) operation of power tools represents a promising solution to problems of excessive vibrations and forces. However, this comes at the price of depriving the operator of the sensory cues used to infer task progression and/or equipment malfunction, which may reduce performance. Branches of power tool telemanipulation call for intuitive operation to make it easy for human operators to transfer from real tools to the telemanipulation interface and simultaneously improve working efficiency.

The complexity of task scheduling and manual assembly involved in production lines provides further motivation for telemanipulation interfaces. Traditionally they require long-term training for operators to learn With the interface, it is possible to provide the operators with visual aids during operation, which is effective in shortening the learning period.

Commercial manufacturers have been exploring applications of virtual reality (VR) and augmented reality (AR) devices beyond games. In terms of warehouse logistics, Vuzix[1] smart glasses improve the process of manual order picking, importing and exporting goods, sorting and packing goods, as well as checking inventory. When controlling a drone, the flying parameters, the position information, as well as video streaming from the drone camera, can all be displayed. These systems continue to grow in popularity and are expected to see more intuitive applications for industry usage. At Ford Motor Co., ergonomics engineers are using VR to establish design criteria related to the maximum allowable assembly force to install various hoses [6].

Given the infancy of VR/AR telemanipulation systems and their broad application range, our focus was to develop and characterize the hardware of a telemanipulation system and apply it to conducting tasks encountered in the real-world environment. Ultimately, the research described here is motivated by the fundamental question of whether VR/AR technology can help to safely operate power tools, and whether the sensory deficits, arising from the telemanipulation context, can be overcome, in part, through the addition of haptic feedback. Our design was based on the following guidelines:

1. In order to mitigate the potentially disruptive effects of introducing VR/AR technology, users should be able to observe and interact with the target object using the display equally well as without it. This suggests that the VR/AR display should offer a maximal field of view (FOV) so as not to limit the visual experience;

2. Although existing generic controllers can be used for telemanipulation tasks, the dif-

[1] `https://www.vuzix.com/Solutions/warehouse-logistics`

ferences they exhibit in geometry and mode of operation, compared to real power tools, may impose extra learning demands on users, with resulting negative implications on task performance. In order to reduce these problems, the geometry and mode of operation of the manipulator of the proposed interface should be as similar to the real tool;

3. Force and vibrotactile feedback are the two dominant forms of haptic feedback generated by power tools in real-world scenarios. It is presumed that these forces and vibrations help operators execute their tasks, and thus, it is important for the proposed interface to provide such feedback as well, allowing us to evaluate their effect on telemanipulation tasks.

During the experiments, we evaluate task performance on a simulated assembly task in a virtual environment, as a proxy for the telemanipulation interface, thus permitting direct comparison of task performance under each experimental condition. This process was carried out in the following four phases:

1. Fabrication of a 3D-printed haptic manipulator, which simulates an impact wrench, and installation of the microcontroller unit (MCU) and associated circuit inside.
2. Development of a multimodal VR telemanipulation interface consisting of the haptic manipulator, a VR head-mounted display (HMD) and a PHANToM Haptic Device, which is able to provide users with visual, auditory and haptic feedback simultaneously.
3. Design and implementation of the tasks in a virtual scenario similar to the real-world situation, which will be executed by human participants during experiments.
4. Analysis of the experimental data for evaluating the proposed system, and gaining insights for further development.

The initial step involved the CAD design and 3D printing of the model of the impact wrench. Following this, we analyzed the operation of the real impact wrench, and summarized its different working conditions. A MCU, four vibration motors, as well as associated circuits was installed inside the 3D-printed impact wrench, in order to simulate the working conditions of the real impact wrench. Each working condition has its characteristic haptic feedback, especially vibrotactile feedback for its high distinguishability, which is generated through the vibration motors.

The second step was to analyze the normal usage of the impact wrench for real-world scenarios, on which the experiments were designed. Similar tasks in the virtual environment for the proposed VR telemanipulation system were designed and implemented. The 3D-printed impact wrench was used as a haptic manipulator to control the virtual impact wrench, seen by human participants through the VR goggles, and executed pre-designed tasks, which simulated realistic usage scenarios of impact wrenches. The intention was to compare performance between different modality combinations of the proposed multimodal telemanipulation interface. This may give foresight for future experimentation with humans, especially emphasizing intuitive HMI.

The concluding phase marks our contribution to the HCI field. The performance of different modality combinations of the proposed interface was compared with regard to the pre-designed tasks. The time of implementing the tasks was recorded. Before and after the experiments, participants were required to complete pre- and post-questionnaires. Through analysis of these data, we wanted to know how much the addition of haptic feedback can facilitate mechanical assembly tasks, and if there is significant difference between the improvement of performance with vibrotactile or force feedback.

1.2 Author's Contribution

In this work, the author created a multimodal VR telemanipulation interface, which consists of a VR HMD (Acer AH101-D8EY Windows Mixed Reality Headset[2]), a 3D-printed haptic manipulator, which simulates a real impact wrench (Campbell Hausfeld TL050299AV), with a main controller (NodeMCU) and the associated circuit. The participant can operate the 3D-printed haptic manipulator to control a virtual impact wrench, seen through the VR HMD, and execute the pre-design tasks in the virtual environment. These phases of the thesis followed a basic framework for scientific specification of a multimodal telemanipulation interface in a virtual environment, borrowing from practices commonly seen in the literature [7, 8, 9]. The final phase of the thesis employed the prototype in nut-installing tasks, for the comparison and evaluation of different modality conditions. The evaluation confirmed that vibrotactile and force feedback can significantly improve task performance

[2]https://www.acer.com/ac/en/US/content/series/wmr

compared to audio-only feedback, but there is no significant difference between them. It also provided insight for future designs of multimodal VR telemanipulation system. Each thesis component was performed individually by the author.

Chapter 2

Related Work

In this chapter, we will begin with a concise presentation of the motivation for this research, i.e., the safety issues involved with the operation of power tools. Following this, we will review the literature of current vibrotactile feedback techniques in an HCI context, VR/AR technology and their applications in industry, and industrial applications with multimodal feedback.

2.1 Safety Issues of Power Tool Operation

The operation of hand-held power tools can deliver significant vibration energy to the hand and arm of the worker, which is a causal factor for MSDs, such as HAVS (also known as VWF) [3]. The development of HAVS relates to many factors, such as the vibration level produced by the tool, the duration of operation, varieties of the tool, operation methods of the tool, environmental conditions, etc. [10]. Short-term exposure to highly intensive hand tasks causes significant slowing in nerve conduction velocity across the wrist [1]. The physical demands related to the operation of a torque-producing power tool is adverse to the musculoskeletal tissues of the upper extremity [2]. Excessive exposure to HTV from powered processes or tools is associated with an increased occurrence of symptoms and signs of disorders in the vascular, neurological and musculoskeletal systems of the upper limbs [11]. With an average of 124,126 injuries per year in the United States, power tools cause the second most injuries out of six items in the tool category [12].

2.1.1 Preventative Measures

A potential way to reduce some MSDs is the use of ergonomically designed hand tools. An auto-feed screw gun with an extension allows the worker to stand upright while maintaining spine and knees in a neutral position to minimize muscle strain and fatigue [13]. These tools may be more expensive but they may save money in the long run by reducing loss-time incidents [13]. For job tasks that require repetitive work, a portable power tool can be used instead of a manual hand tool [14]. Selecting a hand tool that has a power grip or adding a power grip to an existing tool [13] will help employees perform a job task with less stress on their hands and wrists. A portable power tool with a larger trigger requiring the use of multiple fingers to activate the tool will reduce the stress relative to a one-finger activator [15]. Changing the design of the tools' handle can help prevent ergonomic injuries on the job [16]. For example, drywall workers can use an easy-hold glove attached to the mud pan to reduce the hand strain from holding the pan [13]. Another type of glove is a full finger anti-vibration glove used to absorb some of the vibrations caused by a power tool. Pottenger and Benhaim designed a vibration-absorbing brace, which incorporates damping materials to reduce the absorption of energy [3]. However, although there are practical ways for alleviating the risk of power-tool-related injuries, we suggest instead that intermediaries between users and power tools should be utilized in order to solve this issue more effectively.

2.2 Haptic Feedback

In this section, we examine various methods of haptic feedback and some common HCI applications. The literature shows that the goal of haptic feedback, in general, is to communicate information to users and augment simulations or interfaces through the tactile sensation. A broad spectrum of applications includes VR/AR augmentation [17], encoding and transmitting information, and haptics-driven enhancement of user experience [18].

Haptic feedback has a shorter reaction time compared to visual feedback. Providing operators with force feedback was found by several previous experiments to be effective in decreasing task-completion time [19, 20, 21], error indices [19, 21] and energy consumption [21]. Wildenbeest et al. [22] found that low-frequency haptic feedback can substantially improve task performance, while further increasing the haptic feedback quality yields only marginal improvements. This same research also shows that haptic feedback can reduce control effort.

2.2.1 Methods

In this section, we focus on vibration and force in the field of haptic feedback. Different mechanisms have been used for generating vibration, among which the most common ones are linear resonant actuator (LRA) and eccentric rotating mass (ERM). In terms of force feedback, many devices have been proposed, as described in the review by Hayward et al. [23], including a modular feedback keyboard [24], arm exoskeleton system [25], table-top virtual space manipulation system [26], PHANToM [27], force reflecting teleoperated hand system [28], and multimodal mouse [29]. The PHANToM is utilized for our study because of its low cost, effective sensations of interactions and popularity in research laboratories. In this section, we will discuss LRA, ERM, and force feedback devices.

- Actuators:
  - LRA: is a vibration motor that relies on an AC voltage to drive a voice coil pressed against a moving mass, connected to a spring, thereby producing an oscillating force across a single axis. Some models are designed to operate with a fixed magnet and a moving coil. LRAs usually generate their peak amplitude vibration at a particular resonant frequency. The Haptuator, similar to LRAs but with a moving magnet [30], is capable of independent frequency and amplitude variation over a wide dynamic range.
  - ERM: usually consists of a motor and an asymmetric rotating mass attached to it. The magnetic field generated by a DC voltage drives the motor to move the mass around the point of rotation, which results in an asymmetric centrifugal force. The main drawback of ERMs is that the intensity and frequency of their vibration are closely coupled and cannot be controlled independently.
- Force Feedback Devices:
  - The Touch™ Haptic Device (formerly Sensable PHANToM Omni): is a mid-range professional haptic device. It has 6-DoF positional sensing, and can generate 3-DoF force feedback. The OpenHaptics toolkit provides developers with an

API for the PHANToMs to customize their applications. The Premium^{TM} Haptic Device (formerly Sensable PHANToM Premium), is an advanced version of Touch^{TM}, which provides larger workspace and higher force. It can generate 3-DoF translational force feedback and 3-DoF rotational torque feedback, as well as 3-DoF positional sensing.

– The Virtuose 6D [31]: has a similar appearance as the PHANToM and can also offer 3-DoF translational force feedback as well as 3-DoF rotational torque feedback.

– The sigma.7 [32]: is a fully actuated 7-DoF device. A parallel mechanism with 3-DoF actuates the translational motion and an attached wrist with three intersecting axes drives the 3-DoF rotations of the grasping unit, offering another 1-DoF.

2.2.2 Applications

Haptic feedback has been widely used for different purposes. In this section, we will go through some representative applications that involve the usage of haptic feedback.

2.2.2.1 Communication

Haptic feedback can be used to communicate information to users, which can be utilized as a substitute or supplement to other senses. In this respect, the usage of haptic feedback has the potential to improve interaction, especially where the visual modality is overloaded, limited or not available, such as interfaces of mobile and wearable devices or for visually impaired people [33]. The parameters of tactile pulse include frequency, amplitude, duration, location, etc. Through tuning of these parameters, Tactons, or tactile icons, which are structured and abstract messages, can be designed to communicate messages non-visually [33].

Israr and Poupyrev [34] proposed the Tactile Brush, which is an algorithm producing tactile feedback of two-dimensional moving strokes. It is generated with different parameters, such as frequency, intensity, velocity and direction of motion. This algorithm is derived from two tactile illusions, i.e., apparent tactile motion and phantom senstions, and is able to produce high-resolution tactile strokes on skin with low-resolution actuators.

Tsukada and Yasumura built ActiveBelt [35], which is a belt-type wearable interface. ActiveBelt consists of two sensors, which are used to detect the location and orientation of a user, multiple vibrators to transmit tactile feedback, and a microcomputer to control these devices. This interface enables users to obtain directional information via the tactile sense. The authors developed four applications, FeelNavi, FeelSense, FeelSeek and FeelWave, for the purpose of human navigation, location-aware information, search for lost belongings, and entertainment, in which different modes of vibration are used.

SemFeel [36] is a tactile feedback system, consisting of a mobile touch-screen device, with multiple vibration motors fixed on the back, which can generate different patterns of vibration, such as ones that flow from right to left or from top to bottom. SemFeel can inform users about the presence of an object where they touch on the screen, to help with interaction with a mobile device. Through user studies, the researchers found that users can distinguish ten different patterns with approximately 90% accuracy using the system.

NaviRadar [37], which is an interaction technique for mobile phones, is built to inform users of the correct direction for crossings along a desired route, as well as the distance to the crossing. The system consists of a Motorola Milestone cellphone and an LRA, the EAI C2 tactor, attached on the backside, controlled by a Sony Vaio NR11Z laptop through a FiiO E5 headphone amplifier. The single vibrator can generate tactile feedback of distinct patterns to communicate the direction and the distance information of the next crossing, where the user has to turn.

Yatani et al. [38] built SpaceSense, a handheld system for representing geographical information. The system includes multiple vibration motors attached to different locations on a mobile touch-screen device, to generate custom spatial tactile feedback. SpaceSense offers high-level information about the distance and direction towards bookmarked places through vibrotactile feedback to help the user maintain the spatial relationships between these points. A user study showed that participants could maintain spatial relationships between places on a map more precisely, when provided with directional information through both spatial tactile feedback and speech feedback compared to only speech feedback.

Pielot et al. [39] developed PocketNavigator, a navigation system for pedestrians with added tactile feedback. The tactons utilized by the system are called TwoPulse, which uses a pair of pulses to indicate the direction of the next waypoint, and the duration of pause between pairs of pulses to indicate the distance to the next waypoint. A user study involving 301 trips showed that although the tactile feedback of the system had no effect on navigation performance, users interacted less with the touch screen when tactile feedback was enabled [40].

Schirmer et al. [41] developed a shoe-based interface for navigating pedestrians entirely through tactile feedback. The interface consists of a shoe component including a microcontroller unit, vibration actuators on the left and right side of the shoe, and an iPhone app that communicates with the shoe component through Bluetooth. Four vibration pattens are utilized for direction guidance, in which low-frequency vibration on the left or right side indicates turning left or right accordingly, high-frequency vibration on both sides indicates turning back, and no vibration indicates going straight.

Kaul and Rohs [42] developed HapticHead, which makes use of 20 vibration motors forming three concentric ellipses located around the users' head. HapticHead is used for 3D object guidance, in which three motors, closest to the target object, are activated, and the vibration travels along the trajectory as users turn their heads towards the target object. A study showed that users can find virtual objects in 3D space faster and more precisely with the haptic feedback provided by the system, compared to auditory feedback, although visual feedback is even faster and more precise.

Oliveira et al. [43] also developed a head-based guidance technique for 3D environments, which utilizes LRAs for generating haptic feedback. Seven LRAs are fixed on a headband, which users wear around their head, and target azimuth is indicated by directory of vibration and the target elevation is indicated by frequency of vibration. The researchers found that the frequency modulated by a quadratic growth function has significant positive influence on improving accuracy, reducing localization error and reaction times of an active pointing task.

Among the above-mentioned research, two methods are utilized for the indication of direction or position. In the first one, direct mapping between actuators and direction or position is designed, and the vibration of a specific actuator indicates the position or direction mapped to that actuator. This method is intuitive, but it requires a specific amount of actuators to ensure the precision of indication. In the second one, different patterns, modulated by frequency, amplitude, and duty cycle, are designed, which are mapped to directions or positions. This method requires less actuators, but it may require training before users are used to it. Our proposed system aims to facilitate telemanipulation, so the extra mental load from utilizing the non-direct mapping methods is undesired. Further, our pre-designed tasks for the system only requires the indication of four directions. Therefore, the direct mapping method is chosen in the proposed telemanipulation interface.

2.2.2.2 User Experience Enhancement

A major concern of user experience enhancement in virtual environments is highly realistic simulation [44]. Compared to auditory and visual feedback, haptic feedback offers the most intuitive experience for users in the perception of the size, shape, and material of objects constituting the surrounding environment. As examples, Chinello et al. [45] built a fingertip haptic device, consisting of three actuators and three force sensors, and experimented with it on curvature discrimination. Ullrich and Kuhlen [46] utilized one normal PHANToM and one PHANToM with a lightweight palpation pad replacing its stylus to simulate palpation on a virtual patient. Jeon et al. [47] proposed an algorithm, which can simulate probing tumors in a virtual environment through force feedback generated by a PHANToM Premium.

Using a measurement-based approach, Okamura et al. used real contact information with a decaying sinusoidal signal to provide perceptual vibrotactile information about the stiffness of rigid materials, such as wood, rubber, and aluminium [48, 49]. Romano and Kuchenbecker [50] synthesized a wider range of solid materials through reconstructing a signal from recorded samples, which were stored as frequency-domain models after processing. Kim et al. [51] proposed a tactile-rendering algorithm for touch screen surfaces, which is able to simulate 3D geometric features through modulating friction forces between users' fingers and the touch screen.

Culbertson et al. [52] proposed the TexturePad system, consisting of a Wacom tablet and a stylus augmented with a Haptuator, to render virtual textures through synthetic vibration signals. The system first records tool-surface interaction data, which are then segmented and modeled to generate haptic feedback. A comprehensive repository, including 100 haptic texture and friction models, is proposed [53], which can be used to render these textures through an impedance-type haptic interface.

Cirio et al. [44] proposed a vibrotactile fluid rendering model for solid-fluid interaction, leveraging vibration, which is the common physical source of acoustic and vibrotactile phenomena. The model consisted of three components: an initial impact with the fluid surface, a cavity oscillation created when the body enters the fluid, and a set of small bubble harmonics. They illustrated this approach with several fluid interaction scenarios.

User feedback suggested that the model effectively conveys the sensation of interacting with fluids, while highlighting the need for consistent kinesthetic cues.

Wang et al. [54] proposed a method for simulating the exploration and diagnosis of carious tissues in dental operations. Two interaction states, sliding and penetration, are introduced to model the 6-DoF interaction between a tool and a target tooth, A user study shows that the invisible boundaries between tooth decay and healthy tissue can be easily identified through the system. Similarly, Wang et al. [55] proposed an approach to simulate the 6-DoF haptic interaction between a moving hand avatar and a string instrument, in which the string is simulated by a cylinder model, and other parts of the instrument are simulated by a sphere-tree model.

SoleSound [56] is a wearable system designed to deliver auditory and tactile feedback under users' feet. The system consists of two shoes, containing loudspeakers, haptuators and sensors, and a belt unit, containing a microcontroller. Each shoe can measure pressure under the foot and kinematic data of the foot, which are sent wirelessly to the microcontroller in order to generate corresponding auditory and tactile feedback on the shoes. A user study indicates that the system can effectively modulate the perception of the ground surface during walking. Turchet et al. [57] built a similar pair of haptic shoes for simulating walking on different surfaces through audio and haptic feedback. One disadvantage of this work compared to that of Zanotto et al. [56] is that the haptic shoes are wired to a PC and an Arduino, which limits their application scenarios.

Another interesting work by Shin et al. [58], developed a dynamic model to simulate the refrigerator front door through haptic feedback. The system consists of a 1-DoF haptic interface and three software modules for main control, visual, and haptic rendering. Experimental results from tests of the pre-opening, opening, and closing stages of the simulated door suggest it offers convincing haptic experiences, similar to real ones.

Duriez et al. [59] implemented a haptics algorithm for interactive manipulations of deformable virtual objects, in which Signorini's Contact Law and Coulomb's Friction Law are used as a basis. The effectiveness and device independence of the algorithm is exhibited through a virtual snap-in task with two experimental settings, in which the first one utilized a PHANToM, while the second utilized a Virtuose 6D as the haptic device. Similarly, Courtecuisse et al. [60] proposed methods for the simulation of the deformations, cutting and complex contacts of soft tissues through haptic feedback. One major contribution of their work is the GPU implementations of the mechanical computations, which significantly improve the processing time.

Inspired by the previous researches, our system also utilizes haptic feedback to improve the immersiveness and intuitiveness. The vibration patterns of the two working states of the impact wrench, i.e., rotating and hammering, and the collision between the impact wrench and target working objects are simulated by the actuators.

2.3 VR/AR and their Applications in Industry

VR can provide a completely virtual environment for users, while AR can utilize the physical environment as background and overlay virtual objects with it. Both can substitute real objects with virtual ones for quick prototyping. Some of the strengths and advantages of AR [61] are shared with VR, as follows:

- Immersive: AR integrates virtual environments with the real world, while VR implements entirely virtual environments;
- Informative: Visual feedback is typically the main medium utilized by VR/AR, which is effective in transmitting a large amount of information;
- Compatibility: It is possible to integrate VR/AR devices with others for the extension of more functions;

2.3.1 VR/AR Hardware Components

Because of the specific way in which users interact with VR/AR applications, specific hardware is required for driving them. A HMD is utilized in our research, because it can provide immersive experience, and usually does not need to be hand-held. Therefore, we will only discuss HMD as well as its related hardware components in this section. The main hardware components required for VR/AR applications, as well as their individual functions are listed as follows:

- Display device: HMDs, usually fixed on users' heads through a headband, are often used for the display of VR/AR applications. Some HMDs have integrated sensors, such as infrared sensors, accelerometers, and gyroscopes, which are used for gathering users' kinematic data.

- Controller: VR/AR devices require a computer for collecting the data from different sensors, processing and rendering corresponding video output. An external computer is required by some VR/AR devices, which include Oculus Rift, Samsung Gear VR, Windows Mixed Reality, and Meta. Some VR/AR devices have required processors integrated, and can thus run untethered, although typically provide inferior experiences of the simulated environment. Typical devices of this type include Microsoft HoloLens, and the EPSON Moverio.

- Tracking system: It is necessary to gather the position and orientation data of users in order to properly align the virtual elements with their vision. Although HMDs are often integrated with a gyroscope, the sensor itself is usually not sufficiently precise for tracking, often requiring use of external motion capture systems.

- Interaction tools: Interacting with VR/AR applications can be done through traditional input/output devices, such as mouse, keyboard and touch pad, or through more specialized devices, such as remote controllers.

2.3.2 Industrial VR/AR Applications

Virtual and augmented reality (VR/AR) technologies have been used in industrial applications to achieve a variety of objectives, e.g., evaluating assembly sequences [62], guiding users through an assembly process [63, 64], designing and evaluating assembly processes [65], facilitating operation [66], and training maintenance and assembly skills [67]. Moreover, the use of virtual environments was shown to facilitate performance measurements and evaluation of operator performance in direct mechanical assembly [67].

A prototype AR system was developed for aircraft maintenance training and operations support [68], implementing markerless camera pose estimation and an efficient procedure for creating virtual contents and integrating them with the real world. Gavisha et al. [69] evaluated the use of VR/AR platforms for the training of industrial maintenance and assembly (IMA) tasks. A user study suggests that the use of the AR platform should be encouraged and the use of the VR platform for that purpose should be further evaluated. Datcu et al. [70] present an AR-based approach for virtual co-location of a team, which is required for training inflight maintenance. Choi et al. [71] surveyed and analyzed 154 articles published from 1992 to 2015, which are relevant to VR applications on manufacturing.

They conclude that further research is needed to improve the dynamic integration among IT, VR and manufacturing for efficiently supporting an entirely new product development (NPD) process.

Makris et al. [72] proposed an AR system for helping operators working in a hybrid, human-robot collaborative industrial environment, namely, automotive assembly. The system consists of a smartwatch and AR glasses, in which immersive assembly instructions are provided in their field of view along with production data when needed. There are four functionalities provided by the AR solution: assembly process information provision, robot workspace and trajectory visualization, audio and visual alerts, and production data. A case study suggests the effectiveness of this tool in improving the integration of operators with the assembly process.

Peppoloni et al. [73] developed a robot operating system (ROS) integrated framework for telepresence in assembly tasks. The motion and muscle strain of users are captured through a wearable device and reconstructed by a ROS node, which is then used to control the movements of a remote robot arm for manipulation tasks. 3D visual feedback of the scenario, which is augmented with information about the pose of the robot arm, objects in the remote environment and target poses, is rendered to the user through a HMD.

Tripicchioa et al. [74] introduced a real-time panoramic telepresence system for construction machines, which allows for immersive operations in critical scenarios at a safe distance. An omnidirectional stereo vision head, focusing in the current direction of the operator's sight, is utilized to send data to the operator. This is displayed on the operator's HMD, which also provides digital information overlapped with the real world. Hu et al. [75] found the inseparable coupling between working process and quality performance in terms of equipment simulation. Therefore, they developed a VR simulation system, which integrates working process and performance data obtained from different sources, and visualizes them together.

An AR-based interface is proposed for aiding human-virtual robot interaction, which consists of the physical entities in the working environment of the robot, as well as a parametric virtual robot model [76]. A handheld device, attached with a probe, is tracked by an AR Tool Kit method, which allows the users to interact with the spatial information of the working environment. Chintamani et al. [77] proposed an AR cueing method to improve teleoperator performance for display-control misalignment. This method uses an AR overlay of colored axes to facilitate the operation of space robot arms, manipulated with hand controllers.

Due to the extremely small size of devices, fixtures, and layout, different micro-assembly alternatives can be compared more effectively in VR prior to physical assembly. Cecil and Jones [78] developed a virtual environment for micro-assembly, using an automated tweezer, which works as a gripper, and is mounted on a support moving along the z-axis. This system enables the design and comparison of different assembly procedures, and also holds the potential of enabling global collaboration through the integration with Internet.

In the rehabilitation domain, prior research demonstrated the effectiveness of an AR home-training system for treating clinical disorders involving the somatosensory or motor system [79], as well as the efficacy of a closed-loop AR multimodal cueing device for improving the gait of Parkinson's patients [80]. Moreover, the use of AR allows for the performance measurement and evaluation of human participators, which is not possible without virtual components [67].

Previous research illustrates the effectiveness of VR/AR in immersiveness, informativeness, compatibility, and quick prototyping. In addition, VR/AR provides the users with the experience of presence while conducting telemanipulation tasks at a distance. VR/AR can also overlay extra information or guidance about the task on the users' current working environment. Therefore, our proposed telemanipulation interface chose a Windows Mixed Reality (MR) Headset as the display medium, instead of other possibilities, such as video streaming on a monitor.

2.4 Industrial Applications with Multimodal Feedback

Even though humans instinctively attend more to their visual sense [81], haptic and visual systems have distinct encoding pathways [82], and complement each other [83], Therefore, it has incremental benefits to convey the necessary information to the user with more than one sensation. Vitense et al. [84] show that vibrotactile feedback together with visual feedback is beneficial to user performance when performing "drag-and-drop" tasks. Luciano et al. [85] built a system for 3D data manipulation, which integrates haptic, visual and audio feedback, though experiments are required to verify the effectiveness of the system. Sagardia and Hulin [7] built a real assembly task, and gradually replaced each physical module with a virtual one. After comparing all of them on user performance, they found that the haptic modality seems to be the bottleneck.

Webel et al. [67] developed a multimodal platform, which consists of a mobile AR component to provide instructions and a vibrotactile bracelet for the training of maintenance and assembly skills. Since operators mainly use their hands for such tasks, the application of haptic feedback in the hands during training can assist in task comprehension and performance. The developed platform can also be used for sub-skill training and evaluation of the training system.

Ni et al. [86] proposed a user interface for programming welding robots remotely using AR with haptic feedback. A depth camera was utilized to model the surfaces of workpieces in a virtual environment, and a PHANToM haptic input device was operated by users in defining welding paths along these surfaces. Through the proposed AR user interface, a virtual robot was overlaid upon the real robot with respect to the view of the remote workspace shown by the camera, which allowed users to adjust the end-effector pose, and also validate the reachability of defined welding paths. The virtual robot was controlled by the PHANToM, and its end-effector pose corresponded with that of the end-effector of the virtual robot.

Song et al. [87] proposed a teleoperation scheme utilizing human gestures and a multimodal human-robot interface (HRI). A portable hardware called iSpace, consisting of a depth camera, a tactile glove and a HMD, was implemented for haptic point cloud rendering and to support the virtual collaboration with regard to the proposed scheme. There are two steps in terms of the operation of the system, First, the geometry of a teleoperated robot is reconstructed as the 3D point cloud through the depth camera. Second, a virtual environment is generated from the 3D point cloud, in which a virtual teleoperated robot model is shown to users through a VR HMD. The virtual robot is controlled by human operators using their own whole-body gesture, and they are provided with vibrotactile feedback through the tactile glove for facilitating the operation.

Aleotti et al. [88] proposed an AR system for virtual object manipulation in a physical environment, which can be utilized to program manipulation tasks for robots by user demonstration. The system consists of a 3-DoF haptic device, a laser scanner mounted on a robotic arm, a fixed camera, and a desktop monitor. The scanner collects the range data of the workspace as the robotic arm moves along the pre-defined route, which is used for object recognition and registration of the physical environment. The fixed camera streams the video of the real workspace with overlaid virtual objects, which is manipulated by the users with the haptic device. The effectiveness of the programming by demonstration is validated by a realistic scenario, in which the learned task is successfully completed by a robot after user demonstration.

Ferrise et al. [89] developed a simulation environment to train operators for maintenance tasks of industrial products through a multimodal VR system. The system consists of a rear-projected wall display for stereoscopic visualisation of the product, a 6-DoF haptic device for generating both forces and torques, and an optical tracking system to calculate the position and orientation of users' point of view in real-time. In this research, the Multimodal Tele-Assistance (MTA) system was also developed, which enables skilled operators to guide less expert operators from a distance. The system consists of two modules. The first is similar to the above-mentioned multimodal training environment, and the second module is an AR window, in which the remote operator can view the maintenance operations, performed by the skilled operator, superimposed onto the real object.

Bordegoni and Ferrise [90] studied virtual prototyping based on visual, haptic and acoustic elements to replace physical products, which can be used effectively for the communication of a new product, as well as the evaluation of its features. A case study, in which the interactive virtual prototype of a washing machine has been developed and tested, showed that all of the users considered the practice based on multisensory interaction as effective, and the opportunity to express their preferences and immediately try the new version of the product as valuable, which proves the effectiveness of the proposed system.

Although different industrial multimodal systems have been proposed by previous research, very few deal with the telemanipulation of power tools. In addition, none of them utilizes haptic feedback to simulate the tools' working states, which has the potential to improve immersiveness and intuitiveness. General haptic devices with minor modifications are usually used in such systems, leading to fidelity loss of the simulation of the original power tools. Therefore, a customized haptic manipulator is designed and utilized in our proposed system, which simulates the geometric appearance of the original power tool. Multiple actuators on its surface not only guide the users with the tasks but also simulate the working states of the power tool through vibrotactile feedback.

Chapter 3

A 3D-printed Haptic Manipulator and its Characterization

In this chapter, we describe the process of designing a 3D-printed haptic manipulator and offer an overview of its characteristics.

3.1 Design

An impact wrench is a power tool with a socket attached to the end effector, which is usually used to tighten a fastener. Compressed air is a common power source for impact wrenches, although electric impact wrenches can also be seen in the market. Impact wrenches are controlled by a trigger located in front of the handle, and can deliver strong torque immediately using the energy stored in a rotating mass. We designed a haptic manipulator simulating the function of an impact wrench. It weighs less and produces less intensive haptic feedback than an impact wrench, thus decreasing the possibility of musculoskeletal issues.

3.1.1 Mechanical

The Campbell Hausfeld TL050299AV Air Impact Wrench (see Figure 3.1)) has 1.27 cm of bolt capacity and can deliver 338.95 Nm of maximum torque. The impact wrench consists of seven major components:

- Main body: the overall structure of the impact wrench.

Fig. 3.1: The Campbell Hausfeld TL050299AV impact wrench.

- Back cover: the cover at the back, which can be opened for maintaining the impact wrench.
- End effector: the front tip, which rotates when the impact wrench is enabled. It is usually connected to different sockets for different tasks.
- Internal mechanical transmission: the mechanical structure, which absorbs the input compressed air and rotates the end effector.
- Trigger: the mechanism used to control the operation of the end effector.
- Direction-switch push button: used to change the direction of rotation of the end effector.
- Rotary knob: used to regulate the amount of compressed air going into the impact wrench. There are four levels of regulation, and level 1 is the least intensive and level 4 is the most intensive.

The impact wrench has common structure and specifications, which makes it an ideal object for our research. One important aspect of the simulation is the similarity of geometric shape and controlling mechanisms between the haptic manipulator and the impact wrench. Therefore, mimicking the impact wrench is a feasible solution for designing the appearance of the haptic manipulator, and 3D-printing can be used for this purpose. All the major

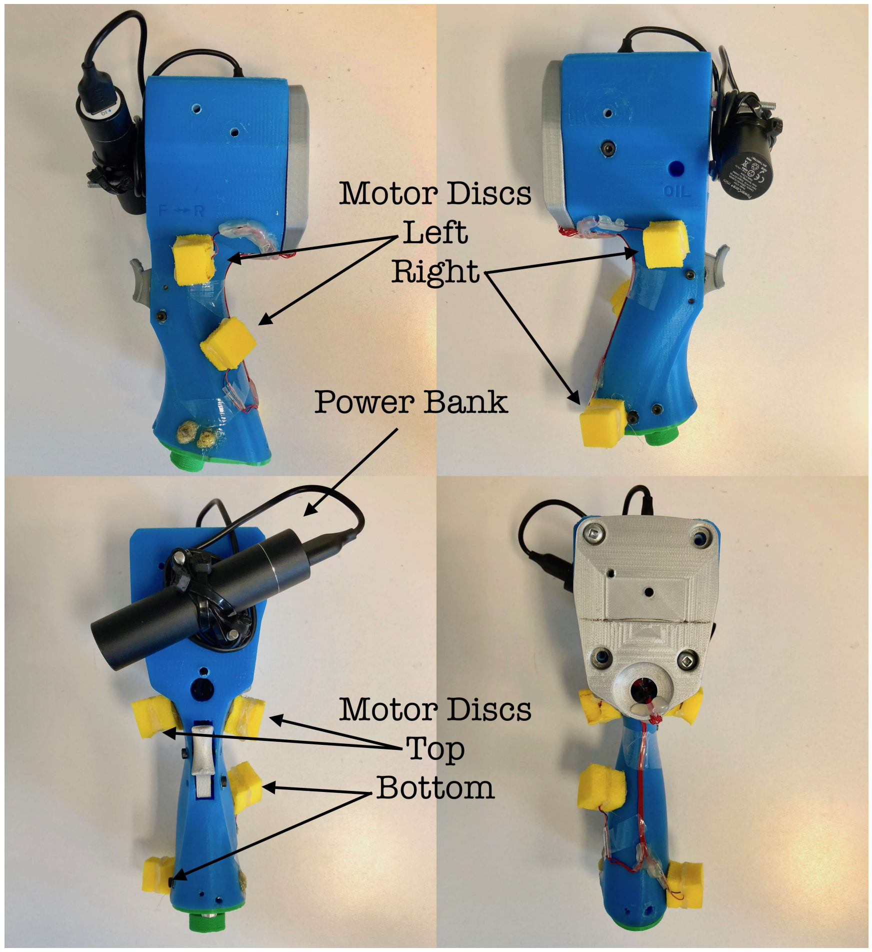

Fig. 3.2: Different surfaces of the 3D-printed haptic manipulator.

components of the impact wrench, i.e., main body, back cover, trigger, and rotary knob are modeled in a 3D environment with Blender,[1] which is an open-source 3D graphics and animation software. Then, each component is 3D-printed, assembled and fixed together with screws to build the 3D-printed replica[2] of the impact wrench, which is used as a haptic manipulator (see Figure 3.2).

Component	Manufacturer	Model Number	Miscellaneous
Vibrating Mini Motor Disc	Adafruit	306-117	3 V, 13700 rpm, 65 mA
Portable Charger	ANKER	A1104041	3350 mAh
MCU	NodeMCU	V2	128 kBytes Memory

Table 3.1: Main electronic components of the haptic manipulator.

3.1.2 Electronics

The 3D-printed haptic manipulator is hollow, and has enough space for putting electronics inside. In addition, the back cover is fixed to the main body through two screws, which makes it easy to open and close. Inside the haptic manipulator, the electronic components consist of a microcontroller, four vibrating mini motor discs, a portable power bank, and the associated circuit, as summarized in Table 3.1. A NodeMCU microcontroller, an Arduino-compatible open-source Internet of things (IoT) platform, includes a Wi-Fi module on the chip, which provides a complete solution for wireless communication without having to connect to external boards. The MCU has 17 general-purpose inputs/outputs (GPIO), of which 11 can be used for connecting external devices. Each GPIO can output a maximum of 3.3 V, and supports software pulse width modulation (PWM), suitable for driving the vibration motors.

The haptic manipulator is controlled by the microcontroller, which monitors the activation of triggers, conducts Wi-Fi communication with other devices, and drives the four motor discs, which are surrounded by yellow foam and glued to the surface of the haptic manipulator, as seen in Figure 3.2. Since the haptic manipulator is made of solid material, vibration at any point can spread over the whole surface, making it difficult for users to localize the vibration. The yellow foam helps constrain the vibration, effectively decoupling the motor discs from the main body of the haptic manipulator. The placement of the motor discs assumes a right-handed operator, as shown in Figure 3.3. This ensures that each yellow foam piece is in direct contact with the user's hand, allowing for the vibration of each motor disc to be distinguishable, and effective haptic feedback to be delivered. Two electrical wires are connected to each motor disc and attached to the microcontroller

[1]https://www.blender.org

[2]Note that we did not 3D-print the front part of the impact wrench, including the end effector, since the user does not directly manipulate these.

Fig. 3.3: Different contact points between the motor discs and a user's hand.

through the hole on the back cover of the haptic manipulator. Each motor disc can generate vibrotactile feedback with intensity and duration adjusted by tuning the voltage output. More vibrotactile feedback can be generated by activating different combinations of discs, which convey different signals to the user.

Electrical power is provided by the portable charger, which is attached to the surface of the haptic manipulator. When the user performs certain operations, corresponding vibrotactile feedback is generated through the motor discs in order to convey an effective impression of the current state to the user.

3.1.3 Host Device

The NodeMCU has enough resources on board for controlling the haptic manipulator. However, it is not able to work as a core processor in a complete system involving complicated scenarios, in which the haptic manipulator interacts with the environment and different working objects, and corresponding responses are required. Therefore, a more powerful computer should act as the host device, providing fast communication with the haptic manipulator. As a communication protocol, we chose to employ Open Sound Control (OSC), originally developed for computers, sound synthesizers, and other multimedia devices, on account of its simplicity, flexibility, and detailed documentation. Specifically, we used the Arduino OSC libraries developed by the Center for New Music and Audio Technologies at UC Berkeley.[3] When users operate the 3D-printed haptic manipulator, for example by pressing the trigger, the NodeMCU sends OSC packets to the host through Wi-Fi, indicating what operation is conducted by the user. The host analyzes the packets, and sends back OSC packets to the NodeMCU based on the current condition of the haptic manipulator, triggering different behaviours, e.g., vibration of the motor discs, as appropriate.

3.2 Characterization

In order to gain insight as to the level to which the prototype could potentially simulate real impact wrench, we analyzed different working states. In this section, since our simulation only considers the impact wrench as a standalone device, without interaction with other objects, we can rely on vibration patterns to convey its working states. Therefore, the corresponding vibrotactile feedback of each of its working state was designed.

3.2.1 Analysis of an Impact Wrench

An impact wrench has two typical working states, rotating and hammering. The latter distinguishes impact wrenches from drills, while the rotating state is similar to that of a drill, in which the anvil rotates continuously and delivers continuous force to a working object. When the torque required to keep rotating the working object exceeds a threshold, the impact wrench begins hammering. Since the duration of each output during the hammering state is very short, the effective torque is difficult to measure, and therefore, difficult to simulate. However, since our goal is to generate haptic cues rather than reproduce the exact values of the generated torque, we refrain from investigating how to measure the actual output torque, and emphasize the methods for generating effective haptic feedback.

[3] https://github.com/CNMAT/OSC

3.2.2 Method

At the current stage, we isolate the haptic manipulator from the environment, with which it interacts, and simply consider its individual working states. Therefore, we need only to simulate the rotating and hammering states of an impact wrench through haptic feedback. This feedback is generated using the four vibration motor discs located on the surface of the haptic manipulator, driven by four GPIOs of the NodeMCU with software PWM. The PWM duty cycle can be expressed with ten bits, and thus ranges from 0 to 1023, corresponding respectively to the intensities between no vibration and the strongest vibration. After several perception tests on participants, we discretized the range into four levels, 255, 511, 767 and 1023, which are clearly distinguishable for users.

We utilized a Teensy 3.2 USB development board and a ADXL 3-axis acceleration of gravity tilt module to measure the acceleration of different levels of vibration feedback, as well as the acceleration of the real impact wrench. The corresponding acceleration for each intensity level generated by vibration motors is 0.0048 g, 0.0728 g, 0.1965 g, and 0.2416 g separately, with the frequency of 39.60 Hz, 84.16 Hz, 99.01 Hz, and 118.81 Hz accordingly. The acceleration of the real impact wrench is 0.3006 g for rotating and 0.3192 g for hammering, with the frequency of 69.31 Hz and 49.02 Hz separately. According to the acceleration data, the intensity and frequency of acceleration decreases as the duty cycle of PWM driving vibration motors decreases. The acceleration of the impact wrench is more intense than the acceleration generated by vibration motors, which satisfies our design goals of generating less intense haptic feedback using the haptic manipulator.

Since each of the four vibration motors can be used for generating vibration feedback, choosing their combinations remains an interesting question. The design space includes the vibration of each motor individually, any two, three, or all four vibration motors, simultaneously. Considering the high distinguishability for each vibration motor because of their location on the haptic manipulator, different combinations of vibration can be used to guide the user towards a specific location. Rotating and hammering states do not provide a perceived direction, so vibrating all the vibration motors can be utilized to inform users of these two states. This saves other combinations in the design space for further interaction. For the rotating state, all four motor discs are enabled simultaneously to generate constant vibration. We tried all four vibration levels, and chose the maximum for the prototype because it offers the most realistic feeling, while not making users uncomfortable because of the damping effect of the yellow foam. For the hammering state of the impact wrench, repetitive pulses are generated with all four motor discs. Different duty cycles for the pulse duration and intensities were tested. After several perception tests, 50% duty cycles and maximum for vibration intensities were chosen for the hammering state, with each cycle lasting for ∼300 ms, according to users' preferences.

Chapter 4

A Multimodal VR Telemanipulation Interface

In this chapter, we describe the design of a multimodal VR telemanipulation interface and its application in a simulated telemanipulation system, which consists of the haptic manipulator, a VR HMD and a PHANToM haptic device. The objective of this interface is to facilitate the telemanipulation of an impact wrench in the real world. Furthermore, we explore the benefits of introducing simple vibrotactile cues, in addition to auditory and low-level force feedback, on users' performance in a VR mechanical assembly task, employing a simulated impact wrench with the system.

Unlike prior studies relying on generic stylus controllers, we used a lightweight, 3D-printed haptic manipulator that replicates the geometries of the physical tool in order to provide greater realism, To the best of our knowledge, our study is the first to incorporate vibrotactile feedback to convey an understanding of the current state of the target power tool, an impact wrench, and also, to notify users of collisions and coupling of the wrench with bolts during teleoperation.

4.1 Apparatus

A desktop computer (AMD® Ryzen™ 7 1700X CPU @ 3.60 GHz, 32.0 GB RAM, Windows 10) is used to drive the VR HMD and the PHANToM haptic device, as well as acting as the host device for controlling each component of the interface and conducting Open Sound Control (OSC) communication with the 3D-printed haptic manipulator.

4.1.1 Head-mounted Display

Fig. 4.1: The EPSON Moverio BT-200 Augmented Reality Goggles.

At the initial stage of this research, the head-mounted display we utilized for the interface was an EPSON Moverio BT-200,[1] as shown in Figure 4.1. The BT-200 runs Android, and consists of goggles for visual display, as well as a controller with buttons and a touchpad for interaction, and processors for driving the goggles. While wearing the goggles, users hold the controller in their hands to operate the BT-200. The advantage of this device is that it can provide all the processing power by itself instead of a host device, and is thus appropriate for mobile applications, which need to be ungrounded. We ran pilot tests with the BT-200 to examine whether it is suitable for the proposed interace. However, a few major drawbacks of this device led to our decision not to proceed with it. To begin with, only the middle of the goggles can be used for display, and its field of view (FOV) is quite limited (23°), which greatly influences the immersive experience. In addition, its processing power is quite limited, which gives rise to noticeable latency when rendering high-resolution scenes. Another disadvantage of the BT-200 is its lack of comfort, particularly the weight on the nose after extended use of 30 minutes or more. To compensate for the weight of the goggles, we attached two straps to each end of the goggle frame separately, and tied them on the back of the users' head. However, this was of limited effect in improving comfort.

[1] https://epson.com/For-Work/Wearables/Smart-Glasses/Moverio-BT-200-Smart-Glasses-%28Developer-Version-Only%29/p/V11H560020

Fig. 4.2: The Acer AH101-D8EY Windows Mixed Reality Headset.

Because of the above-mentioned drawbacks of the BT-200, the Acer AH101-D8EY Windows Mixed Reality (MR) Headset was utilized as the HMD for the remainder of this work, as shown in Figure 4.2.[2] The MR headset is similar to a VR headset, but the major difference between them is that the former integrates two sensors at the front, which allow for precise movement fidelity, and this will be elaborated later. The headset has high-resolution displays (2880×1440 pixels), and a much larger field of view ($100°$) compared to the BT-200. However, to drive the headset, a desktop computer is required, for which the processing power determines the display performance of the MR headset. Therefore, the overall experience of the MR headset, including immersion and smoothness, is improved significantly compared to the BT-200, which enables it to exhibit more complicated scenarios to users. In addition, an adjustable strap of the MR headset, which fits users' head, together with a foam pad, through which the goggles sit on the users' nose, supports the weight of the MR headset, which provides more comfort compared to the BT-200.

Pilot tests show that users can wear the MR headset at least two times longer than the BT-200 without discomfort. Another advantage of the headset is that it has two optical sensors located at the front as well as a gyroscope and an accelerometer, which are able to track the movement of users' surroundings caused by headset movement, and therefore track the users' head. In contrast, the gyroscope and accelerometer inside the BT-200

[2]The matte tape on the headset's surface is used to prevent light reflection, which can reduce the precision of optical motion capture systems.

goggles cannot provide sufficient precision to track the user's head, and therefore, external tracking solutions, such as optical motion capture, are necessary, as well as retro-reflective markers to put on the surface for the camera to track.

There are two major drawbacks of the Acer headset compared to the BT-200. First, it is a VR headset, instead of an AR one, which means that everything seen by the user is virtual and required to be modeled, while for an AR headset, only the virtual elements overlapping with the real world need modeling. Second, the MR headset is connected to a desktop computer, which limits the operational range of the user to the length of the connection cable, which is 4 m.

4.1.2 PHANToM Haptic Device

Fig. 4.3: The PHANToM haptic device.

The PHANToM haptic device, as shown in Figure 4.3, is utilized for generating force feedback in this interface, Specifications can be found in Table 4.1. We fixed a screw to the haptic manipulator with two nuts inside and outside of the top surface, and then fixed the screw to the stylus of the PHANToM using two zip ties. Paper was put between the stylus and zip ties to prevent scratches. The overall mechanism is shown in Figure 4.4. The haptic manipulator is physically coupled to the PHANToM, which, therefore, renders force feedback directly to the users. One advantage of the PHANToM haptic device is that it can track the position of the stylus, making it unnecessary to use motion capture systems to track the haptic manipulator. The drawback is its limited operation range, determined

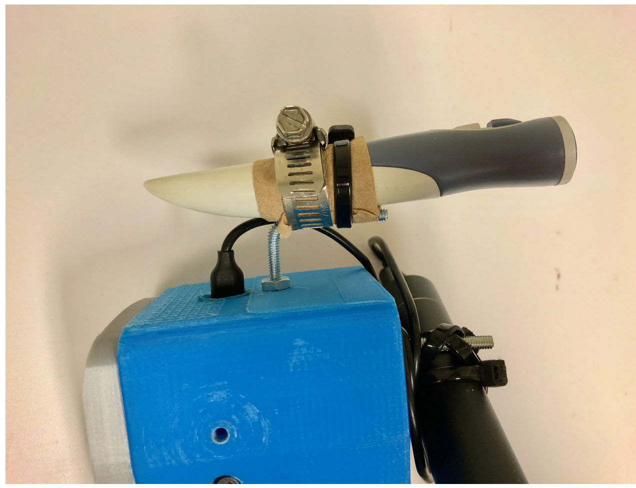

Fig. 4.4: The coupling between the PHANToM haptic device and the haptic manipulator.

by the length of its arms and the angle to which the upper sphere can rotate, which makes it suitable only for tasks requiring a limited operation range.

4.2 Physical Experiment

4.2.1 Task Design

Impact wrenches are used extensively in many industries, such as product assembly, automotive maintenance, house construction, and other scenarios, in which instant torque output is required. Among them, installing nuts on bolts of car wheels is a common use of an impact wrench. During this process, users are required to couple the impact wrench with the target nut first, then press the trigger and push the impact wrench forward to install the nut, which refers to the rotating condition and is similar to a regular drill, and finally strengthen the fixation during the hammering state of the impact wrench. This process covers the two major states of impact wrenches, while requiring users to conduct the coupling between the impact wrench and the target object, also, it is not complicated to set up a physical prototype for this task for experimentation. Therefore, we choose this as a typical task to study in this research.

Property	Parameter
Force Feedback Workspace	>160 (width) × 120 (height) × 70 (depth) mm
Footprint (Physical area device base occupies on desk)	∼168 (width) × 203 (depth) mm
Range of Motion	Hand movement pivoting at wrist
Nominal Position Resolution	>0.055 mm
Backdrive Friction	<0.26 N
Maximum Exertable Force at Nominal (Orthogonal Arms) Position	3.3 N
Continuous Exertable Force (24 hours)	0.88 N
Stiffness	X axis >1.26 N/mm
	Y axis >2.31 N/mm
	Z axis >1.02 N/mm
Inertia (Apparent Mass At Tip)	∼45 g

Table 4.1: PHANToM Haptic Device specifications.[3]

4.2.2 Environment Setup

In order to simulate installing nuts on car wheels in a lab environment, a physical environment was built, as shown in Figure 4.5. The environment consists of two wheel adapters, each of which has four bolts and nuts. The two wheel adapters are fixed to a wood board, which was, in turn, attached to a metal box put on a table. The impact wrench is powered by compressed air through the plastic tube connected to the air hose. A wrench fitting is attached to the impact wrench for coupling the nuts. While installing nuts on bolts, the impact wrench can be in different states, e.g., collision, coupling, rotating, and hammering. The users first approach the nut with the impact wrench in order to couple the wrench fitting with the nut. They may collide with each other several times, and the repetitive force feedback helps the users to gradually couple them. Once the wrench fitting is coupled with the nut, the users can press the trigger to screw the nut. Finally, the impact wrench will generate repetitive impulses when the nut is fully screwed, to indicate the completed

[3]Excerpted from https://www.3dsystems.com/haptics-devices/geomagic-touch/specifications. Note that although the combination of a metal and a plastic zip tie is employed in our design to secure the haptic manipulator to the PHANToM device for maximum stiffness between them, it is possible that this coupling nevertheless reduces the overall stiffness specified in this table.

Fig. 4.5: The physical experiment environment for the impact wrench.

installation.

4.2.3 Experimentation

We designed an experiment with this setup in order to experience the operation of the impact wrench in a realistic scenario. Users are required to stand in front of the experiment setup, wear an ear protector and goggles for safety, and operate the impact wrench to install nuts on bolts. There are eight nuts in total, and beside each one, an index label. For each trial, the user is required to install all eight nuts one by one according to a random sequence of indices, provided immediately before the trial. Triggering of the hammering state of the impact wrench indicates completion of installation. During the experiment, the compressed air is set to 90 psi, and the air regulator of the impact wrench is set to 1, which is sufficient to drive the impact wrench, while not too intense for users' safety. Before the experimental trials, a practice session is given, in which the user can gain confidence in carrying out the task until they feel comfortable. After the practice session, the user conducts two timed trials consecutively.

A total of twelve participants (5F / 7M) aged $22 - 38$ ($\mu = 27, \sigma = 4.92$), voluntarily consented to participate in the physical experiment, which received approval from the McGill University Research Ethics Board with REB#432-0317. The average time taken for each trial among all users is ∼30 s, which is referred to as the benchmark for this experiment.

4.3 Simulated Telemanipulation Experiment

Visual feedback is the expected default in mechanical assembly tasks. The objective of this study is to compare the effects of other feedback modalities, namely, audition, vibrotactile, and force feedback, on completion time and perceived workload of a mechanical assembly task in a virtual environment, This comparison is achieved using a within-subjects experimental design.

4.3.1 Virtual Environment

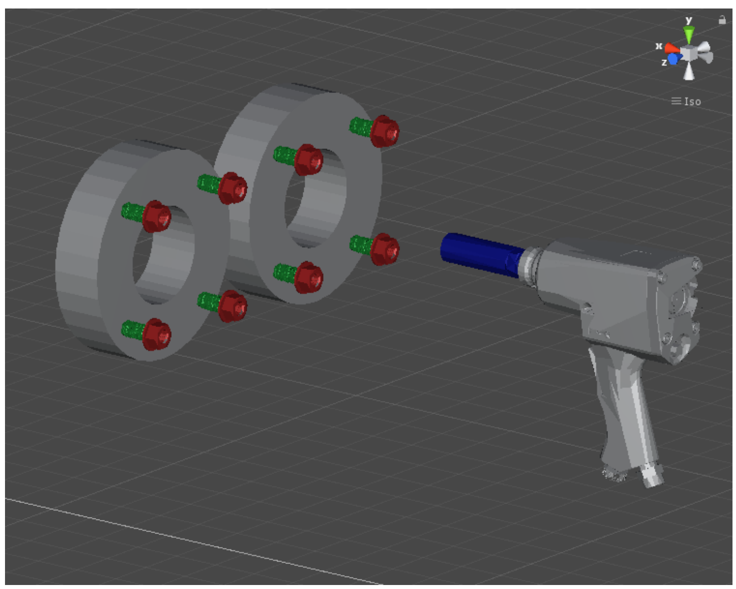

Fig. 4.6: The virtual environment for testing the telemanipulation interface.

A virtual environment is implemented according to the physical experiment setup, in order to test the proposed telemanipulation interface. The model of the impact wrench is the same as that used for the 3D-printing process. The wheel adapters, bolts and nuts are also developed in Blender. Unity[4] is used as the development engine for the

[4]https://unity3d.com/

virtual environment, which monitors the events and triggers related feedback, conducts communication with the haptic manipulator, and drives peripheral devices, i.e., the MR headset and the PHANToM haptic device.

4.3.2 System Configuration

The Mixed Reality Headset requires Windows Operating system with Windows 10 Fall Creators Update installed. The scene displayed by the Mixed Reality Headset is generated by Unity through the building option of the Universal Windows Platform. The Unity 5 Haptic Plugin for Geomagic OpenHaptics 3.3 (HLAPI/HDAPI) [91] was used to synthesize the force stimuli through the PHANToM device. The default settings for generating force feedback are used, which are as follows: Stiffness (1), Damping (0), Static Friction (0), Dynamic Friction (0), Tangential Stiffness (0), Tangential Damping (0), Pop Through (0), Punctured Static Friction (0), Punctured Dynamic Friction (0), Mass (0). The overall virtual environment is shown in Figure 4.6.

4.3.3 Methodology

The PHANToM is placed on a table, approximately 73 cm in height, between the users' abdomen and haunch when sitting. Subjects were required to sit in front of the PHANToM haptic device, and wear the Mixed Reality Headset while holding the haptic manipulator in their right hand, as shown in Figure 4.7. This was done to ensure a comfortable pose for operating the telemanipulation interface, while having sufficient operating range.

Before each experiment, participants were greeted and presented with the institutionally approved consent form to read and sign. They then completed a pre-experiment questionnaire collecting general demographic information and their familiarity with VR/AR and power tools. At the beginning of the experiment, there is a setup process for calibrating the sensors located at the front of the VR headset, in order to precisely track the position of the user's head. After calibration, the Unity program is launched and enters preparation mode, once the user feels ready, the experiment is started. Our research interest is to evaluate the benefit for telemanipulation tasks of integrating different forms of haptic feedback, for which we sample a few of the possible combinations with other modalities. Each participant was therefore evaluated in three different feedback conditions: auditory feedback only (A), auditory and full vibrotactile feedback (A+FV), and auditory, partial vibrotactile

Fig. 4.7: A user is operating the telemanipulation interface.

and force feedback (A+PV+F), representing conditions of successively increasing fidelity of the interaction experience. These are described below in further detail. For feasibility of experimentation, other conditions, such as auditory and force feedback (A+F), auditory and partial vibrotactile (A+PV), auditory, full vibrotactile and force feedback (A+FV+F), are not covered in this research. However, we admit that evaluating other conditions may provide more insights into the effect of haptic feedback in facilitating telemanipulation tasks. Conditions were ordered to allow the presentation of all six permutations across participants (see Table 4.2), with a training phase conducted at the beginning of each of the three experimental conditions.

Once the participants felt familiar with the feedback modality and the operation of the system, the trial for that given experimental condition began. A trial consisted of eight repetitions of the following sequence of actions:

1. In the virtual environment, move the impact wrench to the randomly selected nut and bolt indicated by the yellow arrow (see Figure 4.8).

2. Couple the tip of the impact wrench to the nut.

3. Tighten the nut on the bolt.

4. Move to the next nut and bolt.

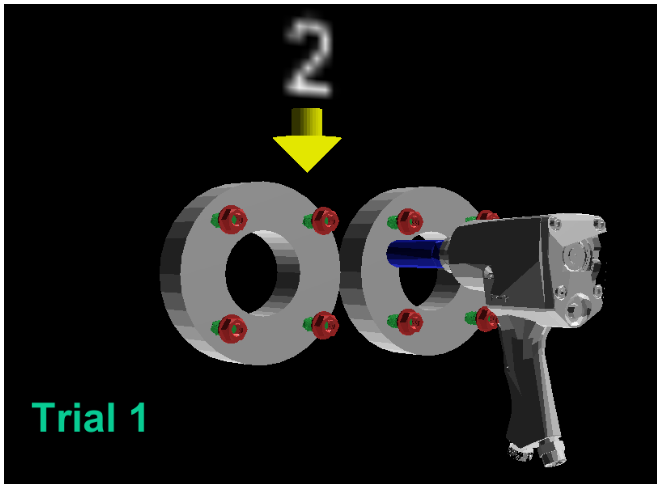

Fig. 4.8: Virtual environment used in the experiment.

After the completion of each trial, participants were required to complete a NASA TLX [92] form before moving on to the next feedback condition.

As a performance measure, completion time for each trial was recorded. A post-test questionnaire asked participants to reflect on their experience, and comment on their perception of fatigue, ease of use, safety, controllability, time required for learning, and intuitiveness of each condition. Experimentation lasted on average 40 minutes and participants were compensated $10 for their time.

1	**A**	**A+FV**	**A+PV+F**
2	**A**	**A+PV+F**	**A+FV**
3	**A+FV**	**A**	**A+PV+F**
4	**A+FV**	**A+PV+F**	**A**
5	**A+PV+F**	**A**	**A+FV**
6	**A+PV+F**	**A+FV**	**A**

Table 4.2: Permutations for experimental conditions. Each of the six permutations was used twice across participants.

4.3.4 Stimuli

Considering the abilities of the multimodal telemanipulation interface for providing feedback, three out of five human senses are utilized: haptic, visual and auditory feedback.

Haptic feedback is rendered through the PHANToM haptic device and the four motor discs, and visual feedback is rendered through the headset. Since the operating range of the PHANToM haptic device is limited, the different working objects in the virtual environment are deliberately placed so that they can be reached. Auditory feedback is presented via a pair of speakers, which are positioned behind the PHANToM, facing the participants.

Trigger	**Auditory**	**Partial Vibrotactile**	**Full Vibrotactile**	**Force**
Collision (with the target nut)	N/A	N/A	50 ms pulse (Two of four motor discs on the collision side (Left / Right / Top / Bottom)	Counterforce in the normal direction of the collision surface
Collision (with other objects)	N/A	N/A	50 ms pulse (4 motor discs)	N/A
Coupling	One-time playback of pre-recorded metallic sound of coupling	N/A	50 ms pulse (4 motor discs)	N/A
Rotation (trigger depressed)	Continuous playback of pre-recorded rotation sound of impact wrench	Continuous vibration (4 motor discs)	Continuous vibration (4 motor discs)	N/A
Hammering (trigger depressed)	Continuous playback of pre-recorded hammering sound of impact wrench	Repetitive 50 ms pulse with 50% duty cycle (4 motor discs)	Repetitive 50 ms pulse with 50% duty cycle (4 motor discs)	N/A

Table 4.3: Events and corresponding stimuli based on the current experimental condition.

Through the HMD, participants could see a virtual impact wrench, as well as virtual working objects, with bolts and nuts highlighted in different colors, as shown in Figure 4.8.

The study included the following experimental conditions, each of which were used to complement the visual display:

1. Audio only (A).
2. Audio and Full Vibration (A+FV). Vibrotactile feedback was used to indicate collisions and coupling of the impact wrench with the nut, as well as mimic its working states through vibration.
3. Audio, Partial Vibration, and Force (A+PV+F). As above, vibrotactile feedback was used to indicate coupling of the impact wrench with the nut and mimic its working states. Collisions were indicated by force feedback, which we hypothesized would contribute to a higher sensation of immersion or presence [8].

As described in Table 4.3, the interface attempted to reproduce various effects including collision, rotation, hammering, and coupling. Coupling between the impact wrench and the nut was considered to be achieved when the distance between the tip of the impact wrench and the nut was below a threshold of ∼2 mm, determined empirically through pilot testing. In addition, collision of the wrench socket with other objects resulted in the transition of its display to a wireframe representation, which informs the users of the collision and prompts them to avoid it.

For each state that involves auditory stimuli, we recorded the sounds of a real impact wrench during the corresponding state, and played it back for the corresponding state in the virtual environment. We observed that the most difficult part of the experiment was coupling the wrench with each nut. In order to provide guidance for this task through the full vibrotactile feedback, two of four motor discs on the handle (Figure 3.2) were activated when a collision was detected, to simulate the initial "tap" one would feel on contact, as follows:

- Collision at the top/bottom/left/right of the indicated nut: activation of top/bottom/left/right motor discs;
- Collision with other working objects or coupling with the nut: activation of all four motor discs.

4.3.5 Statistical Analysis

The weighted ratings from the NASA TLX form were aggregated into an overall perceived workload index [92]. To investigate the influence of the feedback modality on task completion time and workload within subject, a repeated measure ANOVA was employed. A Chi-square test was used to verify the normality of the data, and Mauchly's sphericity test was used to verify sphericity. The pairwise comparisons between conditions were analyzed using Wilcoxon signed-rank tests, and Cohen's d was used to determine the effect size of each pair.

4.3.6 Participants

A total of twelve students (4F / 8M) from McGill University aged $21 - 30$ ($\mu = 25.17, \sigma = 3.04$), voluntarily consented to participate in the study. The pre-experiment questionnaire revealed that the majority of the participants were right-hand dominant (one left-handed, and one ambidextrous). Eight of the participants reported prior experience with VR/AR devices (e.g., Oculus, Microsoft Hololens), while four of the participants had only heard of them. Half of the participants had operated a power tool at least once. Four of the participants were not familiar with 3D manipulation, and three of the participants were not familiar with vibrotactile feedback.

4.3.7 Results

4.3.7.1 Quantitative

Results suggest that different feedback modality combinations exhibit statistically significantly different mean completion times ($F_{2,20} = 4.0849$, $p < 0.05$, $SS_T = 380.19$, $MS_T = 190.1$, Chi-square not sig., Mauchly not sig.). Figure 4.9 shows the difference among all the three conditions. To follow-up on this result, Wilcoxon signed-rank tests were used to determine how each modality combination compared with each other, showing that the completion time for A+FV ($p < 0.001$, Cohen's $d = 1.1944$) and A+PV+F ($p < 0.001$, Cohen's $d = 1.7180$) is statistically significantly smaller than for the A condition. However, the comparison between the A+FV and A+PV+F conditions showed no significant difference. Potential implications of this non-significant result are discussed further in Section 4.3.8..

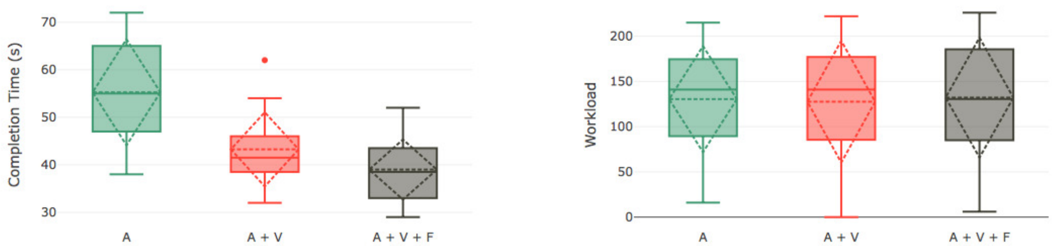

Fig. 4.9: Left: Task completion time distribution per experimental condition. Right: Aggregated perceived workload per experimental condition

Interestingly, no significant differences were observed for aggregated workload data, as measured by the NASA-TLX questionnaire ($F_{2,20} = 0.27871$, $p = 0.75965$, $SS_T = 433.20$, $MS_T = 233.10$, Chi-square not sig., Mauchly not sig.). Multiple comparisons for each element of NASA-TLX were also conducted using Wilcoxon signed-rank tests, but no significant effects were found. The mean and standard deviation of these measurements are illustrated in Table 4.5, and discussed further in Section 4.3.8.

Cond.	Arm Fatigue		Controll-ability		Learning Speed		Ease of Use		How Intuitive	
	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
A	5.92	1.93	3.33	1.15	4.25	0.97	3.58	1.31	3.58	0.90
A+FV	7.50	3.18	3.50	0.90	4.00	0.97	3.42	1.08	3.58	1.00
A+PV+F	7.08	2.64	3.67	0.98	4.25	0.87	3.67	1.15	4.08	1.16

Table 4.4: Quantitative results of post-test questionnaires.

Cond.	Mental Demand		Physical Demand		Temporal Demand		Perfor-mance		Effort		Frustra-tion	
	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
A	6.33	4.48	7.25	4.90	7.92	4.72	7.75	4.65	7.92	4.93	5.42	5.47
A+FV	5.42	4.52	7.25	5.46	6.67	5.05	7.58	5.55	8.75	5.41	5.67	5.40
A+PV+F	6.58	4.48	9.33	5.90	7.42	5.13	7.08	5.66	8.58	5.52	5.67	5.02

Table 4.5: Mean and standard deviation for each measurements of the NASA-TLX.

The participants' opinion of the perceived properties of the system in each experimental condition were collected by the post-experiment questionnaire, summarized in Table 4.4.

Repeated measure ANOVAs revealed no statistically significant differences between experimental conditions for each questionnaire category. Even though it is not significant, there appears to be a connection between perceived arm fatigue and the addition of haptic feedback.

4.3.7.2 Qualitative

Most participants expressed a preference in favor of the A+PV+F experimental condition which they described as presenting a higher-fidelity, and more immersive experience. For example, one participant noted, "The haptic is the best. Because I felt the back force, heard the sound and felt the vibration together, which is really amazing. It mimics the real world ..." [P1]. Another participant mentioned that the vibrotactile feedback increases the realism because it behaves like a physical impact wrench.

On the other hand, one participant mentioned that although vibrotactile feedback improves the overall system, they "[...] personally prefer haptics, audio with a lower intensity of vibrotactile feedback. The main aim is to replicate the real world working of the usage, but to reduce the fatigue ..." [P6], which may suggest the vibration intensity of long-lasting states, i.e., when the tool is spinning, should be reduced, because that is when users can go numb during operation.

Not all participants were positive for the A+PV+F condition. One participant, who has prior experience with impact wrenches and VR systems, mentioned that it took him longer to get used to the force feedback, because it is uncommon for 3D manipulation tasks, and he was not mentally prepared for it. Another participant indicated, "I don't like the haptic feedback, because it increases the workload." [P2]. Similarly, another participant said, "vibration and force both increase the physical demand..." [P10]. This could explain, to some degree, why the addition of vibrotactile and force feedback did not reduce the perceived workload, even though it provided, according to many of the participants, more intuitive interaction.

Both auditory and vibrotactile feedback cues were provided when a nut is fully installed. Two participants mentioned that the auditory cues played a more important role for this action. As one said, "The audio feedback was very intuitive, showing differences in different stages, like pressing, and when to stop pressing, etc." [P4]. This may suggest a bias to attending to the auditory modality when both auditory and haptic feedback are presented in parallel.

4.3.8 Discussion

There are obvious differences between the haptic cues rendered in the A+FV vs. the A+PV+F conditions in response to collision events, most notably, the persistence of force-feedback effect in the latter. Nevertheless, these haptic effects may offer similar information gain. In turn, this may explain the negligible difference in task performance between the conditions, contrary to our intuition, in which force feedback should offer more information gain because of its similarity to the physical world. Users did not complete the tasks significantly faster with force feedback, despite the greater perceived realism of the interaction. These results suggest that mechanically simpler, i.e., purely vibrotactile, ungrounded haptic systems, may support similar performance on VR assembly tasks as their grounded, force-feedback counterparts. This contrasts with previous studies that demonstrated the superiority of force feedback on task performance. However, those studies employed different experimental frameworks and stimuli: no vibrotactile feedback [9, 7], or vibrotactile feedback used only for collision notifications [8], not simulating the working state of the tool.

When looking into the NASA-TLX data shown in Table 4.5, the mental demands of A+FV appears to be lower than in the two other conditions, which accords with the performance improvement of integrating vibrotactile feedback. However, the best performance was achieved under A+PV+F, although not significant, which shows there are other factors contributing positively to user performance besides low mental demand. In addition, the mean of effort and physical demand is higher in the cases where force feedback was presented in comparison with the auditory feedback condition.

In terms of the quantitative results from the post-questionnaires shown in Table 4.4, we believe that the lower level of arm fatigue observed in condition A in comparison to A+FV and A+PV+F is caused by the inclusion of haptic feedback, which involves a more intensive usage of the hand. Subjects reported condition A+PV+F as being more intuitive, which is reasonable, since in the current study, it is the most similar to operating an actual impact wrench. Other post-experiment questionnaire elements, i.e., controllability, learning speed and ease of use, were not found to be different across conditions.

Even though the effect of the proposed vibrotactile feedback on performance improvement is promising, it is important to point out its limitations. We ran a pilot experiment, in which users completed the same task with a real impact wrench in an identical physical environment. The average completion time for the same number of bolts in the same arrangement was in the order of ~30 s, which is approximately half the average time required for participants to complete it using the VR interface. Therefore, we still need to refine our system in order to be competitive with a real impact wrench. Although productivity clearly suffers through our VR interface, it avoids the risk of repetitive strain injuries caused by direct manipulation of real tools, which may be seen as a more serious problem to the individual operator, the employer, and society. Moreover, these results cannot be generalized to all power tools since different effects could be observed in different handle orientations and types of interactions. For example, an air ratchet or angle grinder would not operate in the same way and could potentially be influenced differently by force and vibrotactile feedback. In addition, the simplification of the real world as necessary for rendering in our virtual environment may compromise the effect of the proposed telemanipulation interface on real-world tasks.

Finally, a number of participants suggested that the proposed interface would be an interesting video gaming peripheral. This represents another potential application of our system. These observations suggest several directions for possible future research.

Chapter 5

Conclusion

In this study, the development and application of a multimodal VR telemanipulation interface, which can provide auditory, vibrotactile and force feedback, was carried out. The original motivations of the study came from a need to reduce the risk of injury from operation of power tools, i.e., an impact wrench in this research. Properly focusing the scope of the work, the design space is conveniently narrowed to the telemanipulation interface of impact wrenches. However, because of the sensory deficits during telemanipulation, task performance is usually compromised. The proposed telemanipulation interface allowed us to compare the contribution of different modalities to user performance and experience. Human experimentation involving pre-designed nut-installing tasks was performed for this purpose.

Unlike prior studies relying on generic stylus controllers, a 3D-printed replica of an impact wrench that replicates the geometries of the physical tool was fabricated and characterized as a haptic manipulator in terms of its vibrotactile feedback, lighter mass and geometric shape, mimicking the real impact wrench. Different intensities of vibrotactile feedback can be achieved through PWM waves generated by the NodeMCU inside the haptic manipulator, meaning that the two different operating conditions of an impact wrench, i.e., rotating and hammering, can be simulated.

The haptic manipulator, with a MR HMD and a PHANToM haptic device constitutes a multimodal VR telemanipulation interface. The MR HMD makes it possible to construct a virtual environment that simulates the telemanipulation of an impact wrench. Inside the virtual environment, an impact wrench is displayed to the users, manipulated through the haptic manipulator. Target objects are also shown for the users to work on with the virtual impact wrench. Haptic feedback is generated with the four vibrating mini motor discs and the PHANToM haptic device. The former can simulate the working conditions of the impact wrench, as well as provide guidance for coupling. The latter is able to provide force feedback, which is more intuitive, and can simulate physical constraints of the real world.

The interface was then applied to a simulated telemanipulation task of nut-installation to evaluate the three modality conditions. The proposed telemanipulation interface was designed such that the vibrotactile effects rendered in this study represent not only collision states, but also simplified and attenuated renderings of the vibrations experienced while operating an actual impact wrench. Based on performance results from our study, we can conclude that vibrotactile feedback can significantly improve task performance in terms of completion time, while further integrating force feedback provided negligible gain. Our findings point towards the design of simple ungrounded haptic interfaces that can maintain reasonable information gain, sensory fidelity and consequently, support user performance.

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