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A review of haptic technologies for hardware-in-the-loop development

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A B S T R A C T

Retrofitting haptic technology into existing systems requires a thorough understanding of how haptic technology works. It is essential to select appropriate methods and devices to avoid accidents and losses. A comprehensive literature search was done to investigate haptic technologies over the years to understand their adoption and application. In the current work, the hardware-in-the-loop is of utmost interest, however, the control and software were briefly discussed. The sensors, actuators, and materials used to design haptic devices were explored. Furthermore, specific applications like the intended research, their drawbacks, and possible solutions are presented. However, flexible materials seem to be more versatile in their applications. This may be due to the flexibility, size, and ease of integration. The development of multimodal sensors and feedback was identified to improve haptic system performance.

1. Introduction

Haptic feedback is an ongoing phenomenon changing the narratives in operations, control, and monitoring systems. A major consideration for reality-based operations is eliminating human contact with the physical environment. There are reasons for this but the most explored are safety, limited space or room, multi-functionality adaptation, affordability, sensitivity, and testing purposes. Here, the 3D or 4D model of reality is built, simulated, and deployed to the virtual space with interaction interfaces for the manipulation and navigation of the virtual environment. In such applications, haptic feedback is also well emphasized and deployed in virtual reality (VR). However, for real-life applications, such as in manufacturing and processing, machine reality (MR) is commonly utilized. The MR combines virtual reality (VR), augmented reality (AR), and mixed reality (mR). Therefore, the MR gives real-time streaming of the actual activity being carried out while the user is in an immersive environment receiving the augmented feedback [1–4]. Haptic feedback is essential for human-machine control systems because its accuracy and correct interpretation determine the quality of the information perceived by the human operator in such a hardware-in-the-loop (HITL) system. Thereafter, determines the response accuracy [4,5] of the closed loop system.

Haptic feedback has found applications in most areas of life due to the proliferation of technology, as presented in Fig. 1. Haptic feedback has been found to improve performance in virtual perception [6]. The haptic fidelity dimension framework comprises 14 criteria to ascertain the actualization of the haptic feedback system. Though the initial design is for virtual reality applications, it can be adapted for other haptic applications [7]. This review, therefore, considered the factors highlighted in the framework but not in the same format. These criteria were adapted to suit the present study such that the factors were modified to investigate critical issues relating to our research. These factors are suitability, localization, stimuli, range of force, sensitivity, perception, adaptability, latency, drawbacks, feedback, and control.

In the development of a haptic training and deployment platform for multiple applications, it is important to understand the diversity of haptic systems, which will aid the proper selection of suitable devices and mechanisms to give the best output. These applications are those that link offsite control with onsite operations, especially in areas that are unsafe and deemed unfit for human presence, such as mining and quarrying sites [8–10]. This article focuses on the hardware-in-the-loop aspects of research to present our findings, which will guide our selection of devices for our applications. Hence, we are looking at the hardware components development of the sensors and actuators adaptable for our applications. Haptic feedback is classified into four namely tactile, vibrotactile, force feedback, and thermal feedback.

In our current research in the lab, we are deploying the 6 DOF haptic platform for various applications such as manufacturing [11–13], mining [14,15], medical [16–22] and training [23–26]. All the haptic feedback methods are employed for these applications; hence, it is expedient to review these methods to ascertain the current state and future directions as we strategize for the solutions peculiar to our

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applications. For example, in the mining industry, the excavation operation involves lots of vibrations [27]; here, the vibrotactile comes in. Similarly, the force and tactile feedback are found in advancing the tools and implements into the soil, among other operations [28,29]. Meanwhile, during melting or blasting, the thermal feedback is more prominent than in other types of haptics [10]. In addition, this review will guide us in the design of the hardware-in-the-loop aspect of the research. In the end, the platform will be deployed for training and testing prototypes for various applications.

2. Methodology

In this review, four haptic technologies were examined: tactile, vibrotactile, force feedback, and thermal haptic feedback. To understand the requirements for haptic application, sensors, actuators, and the materials they are made of were discussed. The flow of the methodology is presented in Fig. 2. Software, feedback, haptic applications, challenges, and future directions are presented. The applications under each of these sections are presented, which will assist in the future selection of suitable devices and methods based on these similar applications.

2.1. Types of haptic feedback

In this section, the classes of recent haptic feedback technologies and their applications are discussed as presented in Fig. 3. The type of sensors and sensed parameters are equally examined. This technology is classified into four classes vibrotactile, tactile, force feedback, and thermal feedback technologies. Each class has variables that are measured and the corresponding feedback methods. However, the applications are not limited to only those captured in the figure.

2.1.1. Vibrotactile feedback systems

Vibrotactile feedback systems use vibrations to convey tactile information to users [30]. These systems typically utilize vibration motors or linear actuators to generate vibrations of varying frequencies and intensities. Signals are generated by changing the amplitude, frequency, modulation, duration, and other properties to give the corresponding feedback [31]. The sensitivity of vibration is derived from the impedance adaptation between the vibration motor and the skin [32], which depends on the direction of force, applied area, frequency, and location. The pulse timing method has been used to generate signals from ERM [33]. Electrovibration is also generated when different levels of electric signals are introduced into the device [34]. However, there are recent developments with more versatile approaches using ERMs and LRAs. Some of the haptic feedback systems are based on an event's related potential (ERP) in brain waves for sensation. These two operate on different ranges of parameters, for instance, LRAs have a higher vibration strength of 1.7 than the ERMs with 0.6, but a shorter frequency range of 0 - 200 Hz for LRAs and 0 - 500 Hz for ERMs. In addition, ERMs are driven by DC Voltage while LRAs are driven by Sine Wave (AC). The rise time for ERMs is slower than LRAs at about a ratio of 5:2. The lifetime of the LRA is longer than ERMs, but each is localized on the entire device [31]. They are commonly found in smartphones, wearable devices, and gaming peripherals for providing alerts, notifications, and subtle tactile cues [2,4]. Sometimes, they are equipped with sensors in the form of rings to sense bending, temperature, and vibrations in the fingers or other parts of the human body. These are worn on the upper part of the finger, but the fingertips are exposed for continuous motion detection. Most often, they are integrated with virtual scenarios that enable the user in the immersive world to experience a real scenario [35].

In some applications, they are immersive environments mostly used

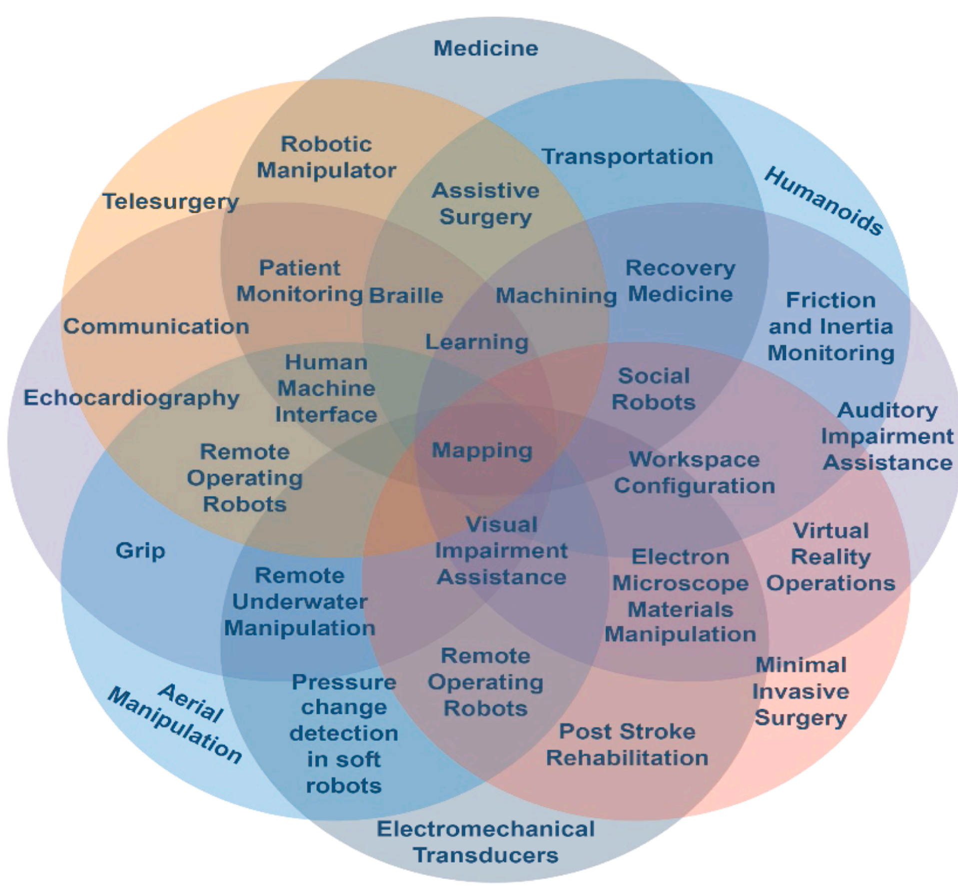

Fig. 1. Some real-life haptic applications.

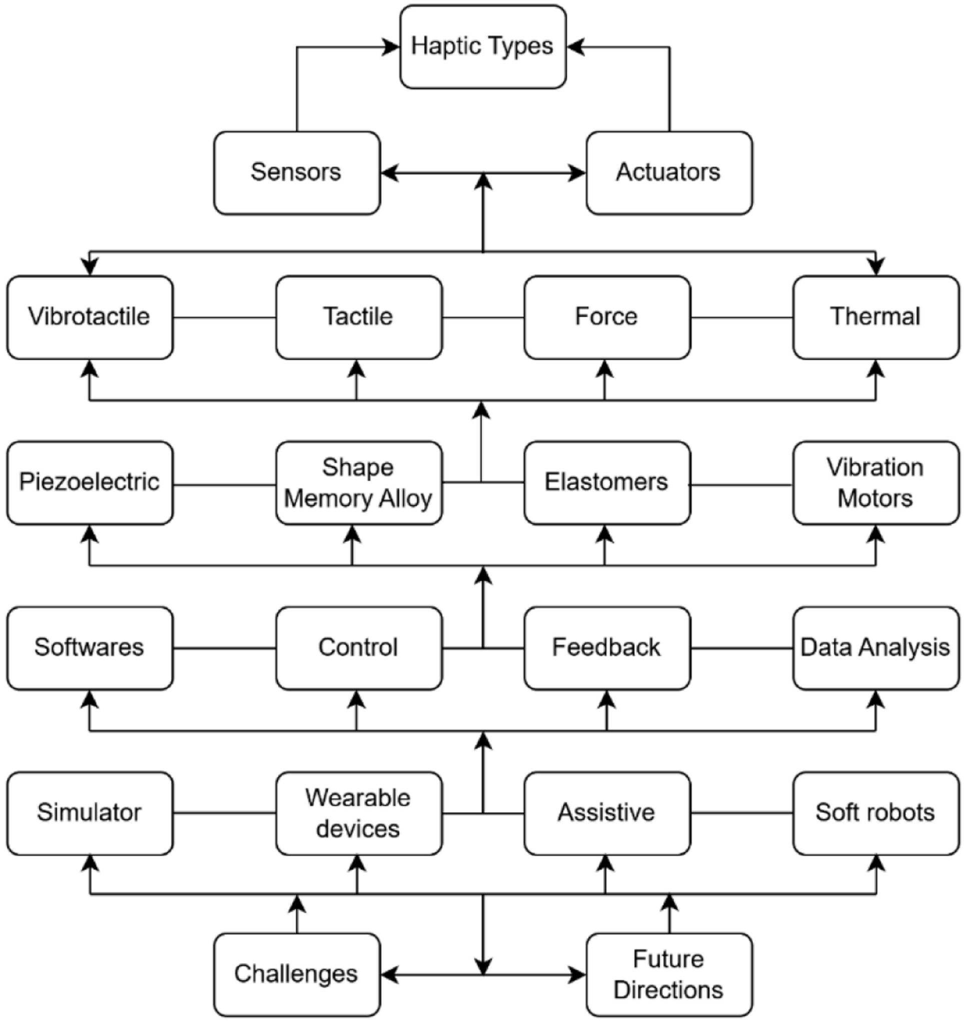

Fig. 2. Haptic feedback review methodology flow chart.

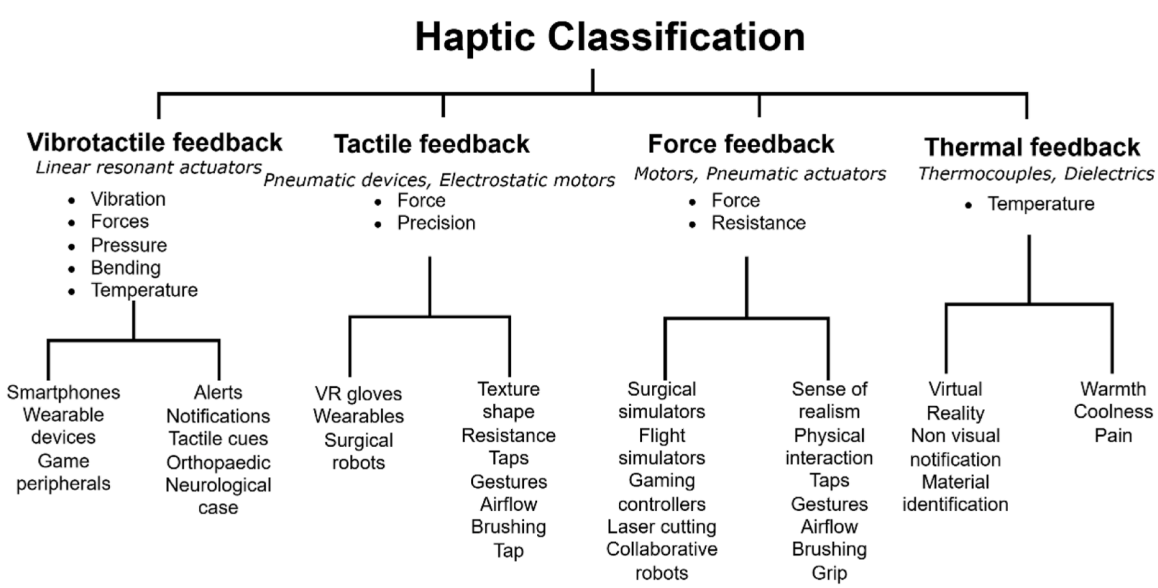

Fig. 3. Summary of haptic feedback classifications and their applications.

in building virtual training simulators [36]. This involves the propagation of forces which are measured to give event-based interactions. Prominent in the vibrotactile haptic is a variety of wearable devices in place of body parts. These have been applied to flight simulations, navigation, gaming, orthopaedic and neurological cases. Stimulations come in various forms and patterns such as vibrations, forces, and pressure [37]. The stimulations from these devices aid the user's ability to navigate assisted devices and virtual objects [1]. The concept of the haptic snake presents features for multi-feedback sensing for taps, gestures, airflow, brushing, and grip. A lightweight collaborative robot that combines all the features to perceive taps, can have the sensors placed at the place of examination [38]. A force-recognition proprioceptive force sensor was developed to provide vibrohaptic feedback for minimally invasive surgical procedures. This system was tested for a porcine heart tissue procedure [39].

Most times, these systems only provide basic sensations in terms of buzz and vibrations [40], which lack the depth needed to simulate complex interactions such as texture and pressure [41,42]. When there are low-density vibrations, it becomes difficult to localize the feedback on the body. In addition, a narrow range of sensations is produced, which cannot represent complex physical properties such as roughness, hardness, or softness. Vibrotactile feedback is widely used for consumer products, and it is difficult to simulate some fine textures and complex interactions, which limits the achievement of precision and localized sensation [43]. Developing adaptive actuators with multi-modal feedback that can provide vibratory and pressure-based sensations is important for vibrotactile technologies. This is very important to address complex tasks found in prosthetics and immersive virtual realities [43].

2.1.2. Tactile feedback systems

Tactile feedback systems simulate the touch sensation by applying force or pressure to the skin. They employ actuators such as pneumatic devices or electrostatic actuators to describe sensations and orientations such as texture, shape, or resistance [44]. Applications include medical simulators, virtual reality (VR) applications [45], and robotic surgery systems, where realistic tactile feedback is crucial for enhancing user immersion and operational precision. Virtual reality environments with tactile gloves worn on the fingers or palms are used for training and simulation purposes [46]. Several devices, such as manipulators and wearable devices, are used for tactile feedback applications. Collaborative robots or multiple sensors can be used to improve the sensing capacity and localization of the system [47]. For example, a lightweight robot to give taps and gestures was coupled with another robot that combines all the features to perceive taps, and each was placed at the two sides of the torso. So, it was possible to capture all the interactions around the body part [38].

To achieve seamless interactions in VR and haptic systems, dynamic passive haptic feedback (DPHF) and haptic retargeting have been used [48]. However, the literature [49] presented a hybrid of both techniques to distinguish perception, especially in weight estimation. It was discovered that the hybrid technique achieved larger proxy feedback. Haptic feedback can be expensive, but the introduction of electrotactile sensors with low power consumption and manufacturing cost is a solution [53].

The tactile feedback control and the interpretation of the perception are most important. Tactile devices are available to be adapted for various applications, hence, the user needs to develop their control and means of interpreting the data received to suit the desired output [50]. The pressure may be too much for the body thereby causing discomfort or pain. This may happen if the pressure is too much or it's poorly calibrated. There have been advancements in resolution and versatility for tactile feedback due to the large surface area available for exploration, but there is a need for scalability for easy integration for compact applications [30]. In addition, it is still a challenge to simulate complex textures at high resolutions because there is no real-time feedback and adaptiveness to respond to dynamic changes as common in surgical simulators [51].

2.1.3. Force feedback systems

Force feedback applies forces and pressure to the limbs or body to simulate physical interactions sometimes with virtual objects [52]. These systems use force sensors or pneumatic actuators to generate varying levels of force and resistance [53]. Force feedback systems are extensively utilized in applications such as surgical simulators [54], flight simulators, and gaming controllers to provide users with a sense of realism and physical interaction in virtual environments. Haptic devices can be expensive, but the advent of electrotactile sensors with low power consumption and manufacturing cost is now explored [55].

Force feedback has been applied largely in medical interventions because it gives a sense of realism [45,54]. Medical applications deal with human lives, it is therefore important to have a good judgment of what the patient feels so that proper treatment can be administered. Most systems can only simulate a short range of forces, and measure forces in different directions and they cannot replicate a wider range of forces but only basic interactions such as resistance and impact [52]. Similarly, developing tools and systems with wider adaptability and a range of applications is urgently needed [56]. Most of them are not portable and less attractive due to their bulkiness. Examples are exoskeletons, gloves, and robotic arms [30]. It is therefore obvious that they will be expensive, given the quantity of materials to produce them. In addition, long-term use of these systems can cause fatigue or discomfort [57]. It is difficult to recreate complex textures, shapes, or motion realistically in real time [30]. Sometimes, they have limited resolution, which reduces their sensitivity to small sensations of touch details like bumps and detailed textures. As stated earlier, they are bulky, hence power consumption will be high. This calls for actuators that are relatively less bulky and cheaper [58]. In addition, force resolution is a challenge especially in wearable devices due to the difficulty in simulating small force variations which are critical in surgical procedures and microsurgeries [59].

Three scenarios of no haptics, the presence of haptics, and exaggerated haptics were investigated. Feedback regarding situation awareness, derived from users' experiences during operation, indicates that significant information is lost when haptic feedback is removed. It was reported that flight simulation improved learning across all applications [60]. However, due to the bulkiness and cost of force sensors, alternative sensing methods have been adopted for haptic feedback. A photoelectric sensor was modelled dynamically using the Stribeck function to capture frictional movements as a function of haptic feedback. For altitude scenarios of hold, gain, and descent simulation, force rendering was simulated using a second-order force calculation to derive a force algorithm that provides the corresponding outputs and displays the effect of force [61]. Kinaesthetic interaction force-feedback is promising in VRs, but they are not suitable for applications that require a large working area. A novel user-gaze-activated kinaesthetic interface mechanical arm device to relocate working space was developed. The VR is used as the visual device and the motion by a mechanical arm force-feedback mechanism. This approach was demonstrated experimentally for object shape identification by exploring strength properties [62].

2.1.4. Thermal feedback systems

Thermal feedback systems modulate the temperature experienced by the skin to simulate sensations such as warmth, coolness, or even pain. They employ thermal actuators such as thermoelectric and thermocouple devices to change the surface temperature rapidly, enhancing immersion in VR environments by simulating environmental conditions or contact with virtual objects. Though tactile sensation seems easily recognizable, thermal sensation has also been adopted in VR scenarios. They come in the form of wearable devices, probes, and heating elements [47,63–66]. Since heat is transmitted through a medium, several fluids have been developed and integrated to transmit temperature differences to the users. For example, a wearable glove liquid metal-based sensor as a motion sensor with haptic feedback capacity was designed to measure finger movements and for vibro-haptic feedback when handling materials with different temperatures [67].

The transmitted temperature changes must be correctly interpreted. To do this, software that models heat interactions, especially Finite Element Analysis (FEA software) with results on displays is used. The thermal feedback system interacts with the surface through a medium and usually requires a medium to transfer and record the sensation. This means the sensor is either wrapped or embedded within the medium. It is important to carefully select the medium such that the data received is as close as possible to the real situation. Hybrid thermo-tactile feedback technologies have been developed [47,68]. One application comprises heating elements projecting heat into a chamber with aluminum foils as covering. This setup was to augment the imagery of ultrasound stimuli as a haptic tactile system. The system was simulated in ANSYS workbench to investigate the heat flow within the system through the palm. Thermal camera images and simulated temperature distribution within the system were recorded. The mathematical relation for the impact of heat on the ultrasound power was also presented [21].

One of the drawbacks of thermal haptic devices is their bulkiness due to the integration of thermoelectric sensors. The response time is slow; hence, it's difficult to simulate dynamic thermal changes like hot objects or cold wind in real-time [47,63,69,70]. Most of the systems have a narrow temperature range that may not capture the full spectrum of the thermal sensations [47]. It is associated with discomfort and may be harmful if the skin is exposed to extreme temperatures for prolonged periods [71]. Hence control and insulation are important.

2.2. Materials used as sensors and actuators

Different materials are used to create haptic sensors for force, texture, temperature, and vibration sensing. Material selection is critical to the performance, comfort, control, sensitivity, durability, and size of haptic systems in surgical simulators, prosthetic devices, assistive medicine, and rehabilitation tools, among other medical interventions. Materials used in medical interventions must be safe, sensitive, and light in weight. Piezoelectric materials, shape alloy memory alloys, electromagnetic materials, soft materials (elastomers, hydrogel), conductive polymers, electroactive polymers (EAPs), vibration motors, and piezoelectric actuators, conductive fabrics, and textiles have been used as haptic sensors and actuators. Material use is based on application. For instance, force feedback devices used in medical applications are different from those used for manufacturing. Medical applications require consideration for feelings and touch sensitivity to skin and tissues but those of manufacturing deal with hard surfaces without feelings. A few of these materials, their applications, challenges, and solutions are discussed in this section.

2.2.1. Piezoelectric materials

Piezoelectric materials can be ceramics or plastic used as sensors and actuators in several applications, such as force feedback for simulators and robotic surgery due to their ability to convert between mechanical pressure or deformation and electrical signals [72,73]. They are found in microsurgery simulation equipment and are used in prosthetic devices due to the requirement for precise force control. They have a high response time and are great with high-frequency vibration generations and compact size. Piezoelectric material development has and is metamorphosizing from single component material, morphotropic material, doped morphotropic materials, Lead-based materials, Non-lead based materials, and pure organic materials, to composite materials. This is achieved by multi-doping, polymerization, and the adoption of artificial intelligence in materials development. The selection of piezoelectric material is a function of the application. However, more effort is geared towards producing high-performance piezoelectric materials through continuous doping with rare earth metals, polymerization with natural composites, and artificial intelligence design and investigation of materials performance [73].

It is not advisable to use them in strain applications like pressure sensors because they dissipate the stored energy quickly to the surroundings which makes it difficult to measure the actual voltage generated [74]. Some of the advantages and considerations of the application of piezoelectric devices are low power consumption, flexibility, ease of fabrication, ease of doping, and biocompatibility [75].

2.2.2. Shape memory alloys

Shape memory alloys as the names imply keep a memory of their shape after deformation; they return to their original shape after being disturbed by external influence [76]. They are therefore used in applications where expansion and contraction are needed [77,78] such as surgical equipment, rehabilitation, and prosthetic limbs to simulate grip force for variable resistance or assistance for motor training [79]. Their applications are also found in aerospace and automobiles as controllers [80], dampers [81,82], ball bearings [83–85], sensors, actuators, grippers, and sprinklers among others. They have high specific strength, high corrosion resistance, high wear resistance, high anti-fatigue strength, and high pseudoelasticity. Though they are known for their good memory effect and precision, they have low heat absorption [86]. They are compact. Lightweight with high power-to-strength ratios. Nickel and titanium alloys are commonly used due to their hyperelastic and shape-memory properties [87].

2.2.3. Elastomers or flexible materials

Elastomers work by shape deformation and measuring impedance between two surfaces [88,89]. It is characterized by simple structure (can be compact), good flexibility, low weight, and cheap [90]. The range of frequency can be broad, but the force range is small (0.1 – 7 N) [91]. Some are made of magnetorheological elastomers (MFEs) which have relatively high stiffness of about 30 – 60 kPa and magnetic fields of 0 – 5 mT. Hydrogel sensors also known as fluidic elastomers explore their high entropy and thermal expansivity to their advantage. They have a wider range of frequency to produce multi-sensational feedback [90–92]. Examples of elastomers are made from natural or synthetic rubber, silicon elastomer, thermoplastic elastomer, thermoplastic polyurethane, nitrile rubber, polybutadiene, and a vast innovative creation [93]. Series Elastic Actuators (SEA) have been applied to robotic systems as haptic feedback mechanisms to replicate the catheter mechanism in non-invasive surgical and telesurgery procedures [94].

They are classified as soft haptics sensors and actuators [90] used for tactile feedback integrated into haptic gloves, and non-invasive medical examinations due to the soothing texture. Owing to the need for enclosure for the fluid and magnetic field range, their coverage span is limited [95]. The liquid crystal elastomers exhibit a smooth texture which has a soothing effect on the skin: this is the phenomenon of laparoscopy and ultrasound scans [96]. Several innovations are being explored to get more functional elastomers with higher performance such as electroactive polymers and dielectric elastomers [90,97]. This is highly necessary because of their flexibility, and they can fit small areas or into irregular structures. The output from the sensors can be improved by employing the correct software and programming such as the lumped-model analysis [98]. Though electroactive polymers are still in the development stage, they possess incredible properties such as high thermal expansivity, high frequency range, and wider force capacity.

2.2.4. Vibration motors

They give tactile feedback in vibrations corresponding to the perceived stimuli of force, torque, vibration, or pressure. They come in different forms, such as small vibrating motors also known as pcb motors, and linear resonant motors (LRAs) [99] used in VR applications to assist in obstacle recognition, object recognition, identification, avoidance, navigation, grip, grab, collision, position monitoring, and other stimuli materials [69,100]. Vibration motors, piezoelectric motors, eccentric rotating-mass actuators, solenoid actuators, and other novel devices [69] are used in haptic applications. They are used in applications for training purposes [101], surgical simulations [102,103], rehabilitation devices [104], prosthetics [105,106], robotic arm applications [107], gaming, flight simulation [108], and manufacturing [109] among other specific applications. It is easy to adapt this material for various applications due to the sizes as adopted in handheld devices, wearable jackets, and haptic gloves. Power consumption may be low depending on the application [69], but has high sensitivity [110]. Timing and actuation affect the discernability of the perception like in the haptic stylus described in [111].

The frequency range of vibration motors can vary between 50 Hz to several hundred Hz depending on how much discrimination is perceived [100,112–114] within relatively low voltages less than 6 V, although there are special devices for special applications with higher values. However, a piezoelectric actuator can utilize higher voltages of 20 V and energy consumption averaging 4 mW but achieves a swift response time of less than 5 ms [69]. Feedback is effective as much as the electro-vibrating principle is properly managed [113]. For instance, the ERM motors are not good for vibration frequency control due to their sensitivity to motor restrain [110]. Pattern rendering, localized spatial rendering, and multiple and multimodal sensing are recommended to improve the application of vibration motors [69].

2.2.5. Specific materials applications

In terms of materials, there is a need to simulate more adopted materials for improved performance such as shape memory alloys, and piezoelectric alloys. These materials need to be optimized for better flexibility, durability, and precision to simulate haptic sensations with compromise in ergonomics, and user comfort. From the control side, latency, and precision achieve real-time control over feedback response which causes misinterpretations or accidents during delicate procedures. It is better to have adaptive controls where feedback is based on real-time changes. Haptic feedback needs to be instantaneous and real-time to allow for accurate control because even a few milliseconds of delay can cause mismatched feedback and loss of control. Hence, the current slow response time experienced in force feedback and tactile systems requires urgent attention.

Special materials have been developed to store information or respond to tactile activities for haptic feedback sensing. A medical implant made with a silicone plate intraocular lens was presented by Smiddy W, 2023 [115]. Another lens for optical performance evaluation was presented with a plate-haptic rotational asymmetric multifocal lens. The lens's optical performance is a refractive intraocular method. It combines several components LS-313 MF15, W-60R, NS1, SY60WF, and NS60YS. It is good for the prediction of intraocular lenses [116]. A shape-changing ungrounded non-wearable haptic device with multiple sensing abilities for convex, concave, and straight shapes. It functions to identify shapes by grasping an object and taking its form to describe it [117]. An easy-to-wear haptic auxetic fabric shape memory alloy was developed. This haptic material was built to provide spatiotemporal and multimodal haptic feedback [118]. A reprogrammable multi-cell-digital mechanical metamaterial was used to transmit signals in a bistable spring [119]. Skin stretching actuation was employed for a reconfigurable hook-and-eye wearable device using strain deformation [120]. Several materials are still needed in haptic feedback interventions. These materials are needed as sensors, storage, and processors to give feedback converted to actions or signals by actuators and human interface.

2.3. Software, control, feedback, and data analysis

2.3.1. Software and control

Software integration is important to haptic stimulus rendering. Rendering is the interpretation of signals generated from sensors and actuators to readable information by the user in various forms such as display, sensory feelings, or action [121,122]. Fig. 4 presents a simple arrangement of the flow of the haptic-software-output interaction. Each summarized block has embedded in it a compendium of vast components and methodologies, and the software is at the heart that gives life to haptic interaction. For example, the stimuli representing haptic devices, tactile, vibrotactile, force feedback, and thermal to sense or read various stimuli, forces, actions, and monitoring operations or activities as discussed in previous sections. This section discusses software integration for haptic technologies, their drawbacks, and possible solutions. Some haptic systems require complex control systems due to the complex mechanical structure of the physical system and kinematic navigation [4]. It is better to have an integrated sensor software system to keep the system simple [123]. Software is used for control, feedback, data integration, and data analysis, however, each of these can be exhibited in various forms.

The application determines the software or algorithm to be used. In

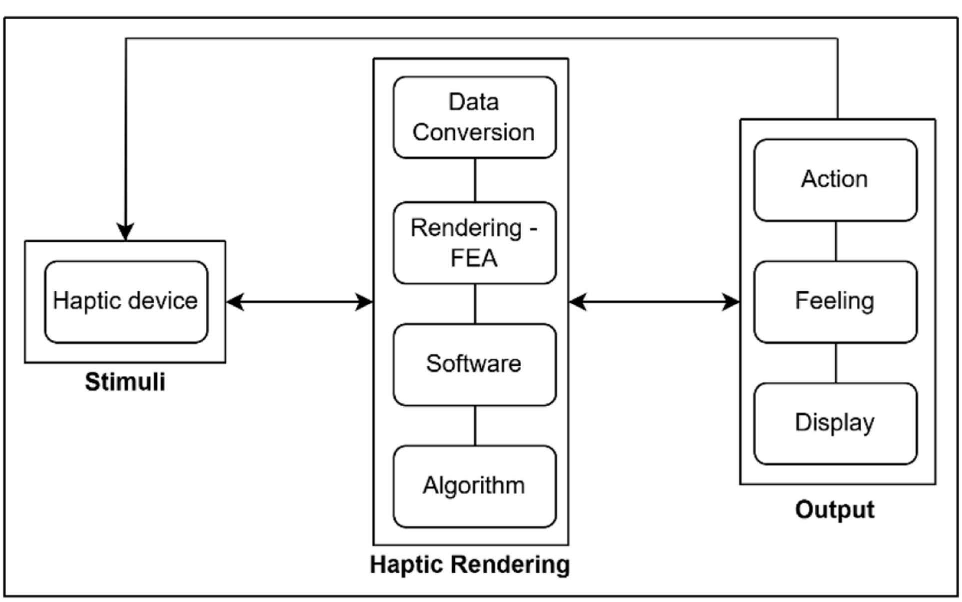

Fig. 4. A simple haptic flowchart.

most cases, force estimation is done by mapping the impedance across electrodes through voltage converters. For example, an AD7276 ADC converter display is integrated with a voltage converter, and has generally known, ohms law comes in handy for most of the electro-based sensors. The line of best-fit curve for this example was estimated with the third-order polynomial regression and a Steed Studio XIAO ESP32S3 microcontroller for control and data communication interface [123], which gave an incredible accuracy. Robotic application in voice tactile using particle filter for improved image and object classification and identification model in a deep neural network was presented. The trained model provides the robot with more accurate tactile prediction; hence the subsequent sampling is improved [124]. The force feedback control system can be enhanced using a noise transfer function helps to overcome the effect of instability. Delta-Sigma control introduces instability at high orders for electromechanical development [125].

In sensory operations, motor actuation, weight shifting, elastic interfaces, and exogloves are essential components for multimodal kinaesthetic feedback [126]. For motor-actuated devices, feedback propellers are arranged along the force measurement line of action on the wearable gloves. Some of the software used for haptic applications is presented in Table 1. Some of these will be discussed in this section.

For pronunciation improvement, vibration motors were embedded in a wearable finger haptic glove which measures acoustic difference between a pre-set voice parameter and the speaker voice. The control and coordination were implemented with Mel Frequency Cepstral Coefficient (MFCC) and Dynamic Time Warping (DTW) transmitted through tactile codes [127]. Similarly, haptic feedback was applied to obstacle avoidance, object monitoring, and control. For example, in large transportation management, obstacle avoidance was tackled using haptic belts with embedded vibrotactile sensors. Obstacle proximity and location are recorded by the feedback module to give situational awareness during transportation [128]. Furthermore, a continuously variable transmission (CVT) alternative variable actuator was used for a Human-robot Interface (HRI) managed by an optimization algorithm and static force analysis [129]. For remotely operating robots, pseudo-haptic techniques for multimodal technique assisted in improving teleoperation of remote vehicle driving, objective maneuvering, situation awareness, and collaborative tasks [130]. Gaussian friction model for nonlinear (virtual stiction, and stribeck effect) using stability equations with different time delays and virtual damping results in good precision [131]. Optimized torque distribution in a workspace configuration was achieved using a 3 DOF spherical parallel robot haptic device. An additional motor enhanced the proficiency starting configuration for an exceptional torque distribution [132]. In parallel robotic control, forward and inverse kinematics are used to describe the linear and angular rotations and positions of the gripper sensors to measure the force feedback. The geomatic touch sensors used show that it accurately recorded the force feedback with accurate position mapping [133,134]. Efficient control of haptic feedback systems can be achieved through wearable body devices laced with sensors that make impacts on the body corresponding to the force sensed in the form of punches or slashing. Because the surface area of the human body is wider, an impact vest fitted with nine impact actuators generates effects per position, duration, and conditions about the specified manipulations [135]. Feelix is a tool that describes the perceptions of designers while engaging in the development of feedback systems. This tool can be explored by designers and developers because it aids appropriate drafting and refining of the responses of the feedback system [56].

Table 1
Some software applications for haptic interactions.

Authors	Haptic device	Method/ software/ hardware	Feedback	Stimuli
[132]	Controller	Variable and non-linear damping	Time delay and feedback signals	Force coordination and position
[133]	Wearable EEG	Surface Vector Model (SVM), Random Forest, and Neural Network	Time and frequency	Surface texture (smooth, rough, and liquid)
[134]	VR simulator	HMD controller	Heartbeat rate	Heartbeat
[135]	Haptic robot	Visumotor perturbation	Task segmentation	Gesture
[136]	Vibration motor	Mel Frequency Cepstral Coefficient (MFCC) and Dynamic Time Warping (DTW)	Control coordination	Voice and sound
[137]	Vibrotactile sensor	Haptic bells	Texture signal	Object recognition and obstacle avoidance
[138]	Variable actuator	Optimization algorithm and static force analysis	Interaction	Continuously variable transmission

2.3.2. Data analysis and artificial intelligence

Multimodal feedback has been studied for multiple haptic sensing operations. Integrating multimodal feedback for all feedback, including visual enhances task effectiveness [136]. An example was reported by [137,138], with Tangible User Interfaces (TUIs) incorporating Hidden Markov Models for gesture recognition with Smart Micrel Cube (SMCube). This method was equally tested for multiple users and the performance followed comparatively with the usual forward algorithm. It was therefore recommended for low-cost, low-power, non-floating microcontrollers. In addition, the successful performance of the algorithm can be a function of the number of bits adopted for data representation [139]. Since there is no framework for the usability of haptic systems, the correlation between user experience and perception, statistical analysis such as ANOVA [140], frequency distribution, standard deviation, and variance are used to categorize and classify outputs which are then interpreted according to the set objectives. Hypothesis testing, correlation, and regression analysis are also employed for the validation of results [70,140].

As stated earlier, weight shifting is essential in haptic object orientation and shape identification, and this was achieved by developing a fluid vessel for fluid mass in cylinder sensation, which can be balanced horizontally and vertically [141]. A haptic feedback-enabled EEG examination experimental setup to incorporate data acquisition hardware and software, data logging software, and a monitor screen in a unit was presented. The system adopted OpenBCI hardware and its software while the graphs were plotted on a 19-inch LCD monitor for data collection, signal processing, feature extraction, classification, and feedback in LabVIEW. The EEG cap used had 8 electrodes and 250 Hz sampling frequency, and 6 nA input current bias for the data collection. The range of the cut-off frequency was 58 and 62 Hz for the notch filter. The alpha and beta bands were preserved by setting the band-pass filter to range between 7 and 30 Hz. In the feature extraction module, the Common Feature Pattern (CSP) filter was adopted, and a 1 s epoch was sent to the classifier every 0.0625 s. The Linear Discriminant Analysis (LDA) data analysis tools were used for classification because of their superior performance compared to the Support Vector Machine (SVM) and Multilayer Perception (MLP). Two sets of feedback were recorded: visual feedback and kinaesthetic haptic feedback. The feedback was analyzed and displayed on the monitor screen as discussed earlier with all parameters measurement in a single unit as a multimodal system [142]. Electromechanical transducers are used for soft robots, artificial muscles, loudspeakers, and haptic devices in automotive applications. Conical Dielectric Elastomer Actuator (DEA) was introduced into a rotary knob development. The components of the driving voltage were altered to accomplish variable torques for automatic control with unique detents and sensations [143]. Similarly, controllers with variable damping and nonlinear damping using online data capturing of time delay and feedback power signal to obtain coordination of force and position simultaneously were reported [144]. A touch wearable EEG-based texture discrimination was developed to identify the state of the surface in terms of smoothness, roughness, and liquid. The brain state haptic feedback was acquired from the time and frequency data. The data was classified using ensemble classifiers Surface Vector Model (SVM), Random Forest, and Neural Networks (NN) [145]. In the echocardiography diagnostic training for medical students, a VR simulator coupled with a head-mounted display was provided. A haptic-enabled interactive HMD controller monitored the simulator [146]. Assistive learning was improved by introducing instructional stimuli. Nonintuitive visumotor perturbation with the use of different motor strategies was implemented for the task segmentation learning technique. The introduced haptic system improved the accuracy and precision of learning [147].

2.3.3. Feedback

Haptic re-appearance methodology was applied to allow for accurate feedback when dealing with tissues in non-invasive medical procedures from the VR standpoint. In this system, an external force imposed by the operator in the immersive environment gives a more effective assessment of the actual state of the paths and the interactions of the medical device [148]. Adoption of artificial intelligence such as reinforcement learning, neural network, surface modeling has been shown to improve the simulation of haptic feedback. These methods allow the system to be trained with previous data of successful localization and this results in accurate simulations, hence good results [149].

Novel methodologies were developed for haptic feedback controls. A 7 DOF 2-delta-like translators were arranged parallel to a helical handle to generate translational and rotational motions to achieve haptic transparency. The system showed accuracy in free space and high force capability in contact [150]. Haptic feedback trackers as head-mounted displays, gloves, and pedals for visual, auditory, tactile, and kinesthetic feedback were implemented for a humanoid robot [151]. Human reaction time compensating haptic-based bilateral teleoperation strategy using a 4 DOF was reported for aerial manipulation [152].

The feedback is central to the acceptability and performance of a haptic setup. Efforts must be made to achieve the best feedback possible as it affects operation, the perception environment, and the safety of users. For feedback monitoring, Fingertip aero wearable haptic for virtual space monitoring of multi-channel micro-airflow chamber by exploring tactic feedforward control was discovered to integrate cognitive models and tactile feedback cues for perceptual deficiencies in VR [153]. For unstructured machining, the HCI was enhanced using Scalable Motion Mapping (SMM) Variable Admittance Control (SAC), and Elastic Concession (EC) to damp fluctuating cutting force and eliminate cognitive strain [154]. A hybrid actuator comprising a Shape Memory Alloy (SMA) and Soft Pneumatic Actuator (SPA) providing a memory effect was developed to improve the emotional and haptic capacity of social robots [155]. In the Scanning Electron Microscope (SEM) machine, visual feedback is not sufficient for micro-nano materials manipulation in the scanner. A nanorobotic haptic feedback system for multiscale manipulation, management of force, and position control was introduced, which reduced the exertion of excess force on the material [156].

3. Wearable/attachable haptic devices

Haptic feedback mechanisms are mostly designed to be wearable on the hand, fingers, body, and head. The part of the body to put the devices on depends on the application field and the feedback desired. They provide sensory, monitoring, and coordinating activities. These devices have been demonstrated to measure or apply stimuli in several physical and virtual reality applications. A few of the applications, first on machine and physical applications, then on medical applications are presented. The pressure generated by head-worn wire hangers was reported to create similar multiple illusions when worn on other body parts [157]. Natural materials have been explored as flexible haptic devices. For instance, a strain-sensitive adhesive made of wearable core-shell architectures from natural basil seeds was used as an injection on the skin for a human-metaverse interface [118,158]. Similarly, in energy harvesting, seedless vertical nanorods made of high piezoelectric material were used for haptic sensing [159] and to control passive feedback and measure stiffness with a wearable spring-based monitor [160]. In machine interface applications, to improve operator awareness in manufacturing and device manipulation, a wrist vibration haptic device was introduced [161] and a robotic touch surface for manipulation in a virtual room was adapted, which supports mid-air planar interactions [162]. Also, air charge haptic methodology was described using accumulated air which magnifies the principle of accumulated air momentum to amplify underground impact force [163]. In addition, 3D-ElectroZip touch wearable sensor was made with dielectrophoretic liquid zipping actuation to give multidirectional force feedback by measuring the normal and reactional forces [164]. Furthermore, a wearable vibration device controlled through transmitted tactile from a smartphone was developed for visually impaired individuals [165]. Neuromuscular Electrical Stimulation (NMES) wearable haptic device applied in force feedback applications for lifting objects was tested on two scenarios: using physical strength to lift load versus electrically stimulated perception to describe kinematic response, metabolic and fatigue characteristics [166]. Lastly, in a Human-Computer Interface (HCI) interaction, WindCheck, a wearable heartbeat emotion status regulator that regulates emotions, can be modified to provide more possibilities beyond regulation [167].

The medical field had its fair share in these applications due to medical procedures' high precision and delicacy. For example, a 3D-printed robotic haptic finger was developed to measure force and pressure from medical diagnostic machines [168]. A wearable Electric Muscle Stimulation (EMS) for biomechanical stimulation which translates torque to muscle stimulation through ErgoPulse Kinesthetics force feedback, was applied to the lower body electrifying [169]. Rigid architecture tiles were arranged into body shapes for biological protection for tremor suppression intervention controlled by programmable tessellation [170]. In the assistive colonoscopy clinical practice, the HMI of the intraluminal robot impacts clinical performance. Haptic serial-kinematic devices comprise Virtual stimulators and wearable sensors to measure cognitive load, data collection units, and questionnaires for impression and perceived stress [171]. An intervention for telesurgery, point-to-point trajectory planning, was introduced to a Quasi-spherical parallel manipulator [172,173]. Meanwhile, in a non-invasive medical procedure, probes are either inserted in the human body or placed on the parts of the body being investigated. These probes are usually hand-gripped and navigated professionally to areas of examination. Hands and grippers in the form of two fingers with fused force sensors were incorporated into a robotic arm for remote spatial interaction. The haptic sensors enabled the grippers to hold objects without dropping them [174].

4. Challenges and future directions

Some of the challenges and future work have been discussed in previous sections, however, cogent and pertinent ones to the ongoing work have been emphasized. In wearable devices, muscle distribution configuration is still a challenge because it is difficult to generalize. It is, therefore, preferable that the design should allow for direct installation onto existing clothing. Some of these wearable devices make use of artificial muscles to mimic deflections like human muscles. Individual differences and the location of artificial muscles can result in varying sensitivity [175,176].

The major drawback for thermal applications is the slow response time and low resolution [177,178]. Closely related are variations in sensation due to user intuition, which is more prominent with very low temperature variations. More should be done to improve the efficiency and responsiveness of thermal actuators. This issue is prominent in immersive and real-time experience applications as found in gaming and robotics [178]. Faster thermal response time is essential; hence, developing materials with better thermal conductivity and faster response to thermal changes is highly desirable to overcome sluggish feedback. The use of localized thermal elements can provide more controlled feedback for improved comfort and risk of harm. Leveraging thermoelectric elements can rapidly improve response time and feedback and create more realistic thermal feedback. Power usage should be considered in developing haptic mechanisms for certain locations like mining sites [179].

Multisensory devices have been reported to improve accuracy in applications according to Wu et al., who reported better accuracy when an artificial multisensory integration was compared with a single sense device [180]. They introduced a flexible triboelectric nanogenerator with an organic photo synaptic transistor in place of a lead-free perovskite quantum dots single-sense device.

Current vibrotactile systems can be improved by increasing the frequency range and precision of vibrations to improve fidelity. However, multi-frequency actuators arranged like strain gauges can be adopted to simulate a wider range of sensations. More sophisticated vibration arrays on wearable devices can be introduced to improve localization and create accurate interactions, developing compact actuators with high-fidelity [181]. Similarly, combining vibrotactile feedback with other sensory inputs such as visual and auditory cues can improve the realism and immersion of the haptic system [38,40].

Using high-resolution actuators improves sensitivity to detailed and realistic sensations. For example, if the better tactile array for gloves, wearables, and touch screens are used [181,182]. Investments in electrostatic microfluidic or soft actuators to develop more subtle and varied textures and sensations. In addition, smart materials such as shape memory alloys or piezoelectric elements can improve the system's ability to create varying textures and sensations dynamically. Based on force feedback, several haptic teleoperation systems have been implemented for insertion needles in magnetic resonance imaging. These flexible needle control and cutting tip force for ultrasound procedures were delivered through both kinaesthetic and vibrotactile feedback [183].

This type of system can be used for shape recognition and management. Shape-Haptics is a force-displacement haptic feedback system for passive feedback on physical interfaces. A model was created through laser cutting from acrylic plastic. The shape is drafted such that it is easy to customize for specific applications and to allow for a smooth sliding profile during interaction [59]. In another research, collaborative assistive robots equipped with magnetically actuated, magnetorheological haptic feedback sensing were deployed for non-invasive surgery. This novel technology is beneficial in reducing workload and reducing surgery time [184].

In surgical procedures such as laparoscopy, grasping is the most essential task tactfully when manipulating surgical instruments during such procedures. This task cannot be accurate without an accurate sensory system. To prove this, three modes of operation were conducted: visual only, haptic only, and dual visual-haptic mode. The dual mode exhibited the best feedback threshold, followed by the haptic-only [185]. Lighter and more compact high-power actuators need to be developed to improve the range of sensation. Research should be done to develop more ergonomic wearable devices, for comfort and portability. Soft robots as innovative and smart flexible actuators should be developed and implemented to reduce bulkiness and improve comfort while functionality is not jeopardized. The adaptability of these systems can also be explored, such that user preference or real-time conditions are considered to minimize fatigue and discomfort.

Feedback without delays and latency is still a major challenge in haptic operation, and a few suggestions have been made with the potential to reduce this. For example, Ivanova et al. 2021 [186] proposed a human-like interactive controller to mitigate the effect of feedback delay. Artificial intelligence is a promising approach to be explored such as ensemble deep learning [187], Neural Networks based algorithms (LSTM, CNN, R-CNN) [188], Autoregressive (AR), Autoregressive integrated moving average (ARIMA) [189], Vered and Elliot, 2023 proposed the use of digital twins to compensate the backlash and re-design the dead zone. This system is designed to mimic the real environment, and real-time response is measured and updated on the digital twin [190].

A vital consideration in the haptic system is environmental interference and several methods have been explored to mitigate this effect and ensure stability. One method that has been used is the admittance adaptive method based on the variation between the experience of the pressure on the slave and the master side of the system. Space variation causes a stability issue, but an adaptive algorithm using the theory of passivity showed good prospects for remediation [191].

5. Conclusion

In this work, we have examined the types of haptic feedback systems available and the sensors and actuators used for haptic feedback. All the types can be applied for operating manufacturing and process plants onsite from offshore locations. To further understand and help the choices, the materials used in this haptic feedback were examined with their applications, current state, drawbacks, and future directions. A few case studies relevant to the research focus were also considered, which provides a good foundation for initiating the adaptation for the industries intended for. In the 6 DOF VR platform, the steering, pedal, and pedal are installed, and the user will wear a haptic jacket. However, with the current study, there may be a need to incorporate additional wearables such as gloves and custom bands based on the application and simulation intended to capture.

Each of the types of sensors and actuators is capable of adaptation in the intended system. Simple and flexible devices such as elastomers, electrotactiles, and LRAs found much use due to their size, flexibility, and cost. The following are some drawbacks common to most of the types of haptic systems and materials. Recommendations for improvement are also presented.

- Difficulty in localized stimuli and texture identification. This can be solved by modifying the sensors.
- Complications when multiple stimuli are to be captured. The introduction of multimodal sensors and actuators is proposed. In addition, a combination of different types of haptic sensors and actuators can be introduced.
- Limitations in materials capacities. The development of custom materials and hybrid materials is suggested. Since data extraction is by software, modifying the software used can also improve performance.
- Bulkiness of certain sensors and high power consumption were also noted. Research into compact and low-power materials is encouraged.

CRediT authorship contribution statement

Oluwaseun Kayode Ajayi: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Shengzhi Du:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Syeda Nadiah Fatima Nahri:** Writing – review & editing, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that there is no conflict of interest.

Data availability

No data was used for the research described in the article.

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