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FROM KINESTHETIC SENSE TO NEW INTERACTION CONCEPTS: FEASIBILITY AND CONSTRAINTS

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Abstract

Nowadays designing tactile stimulation devices requires lesser efforts, tools and skills than needed to create a mechanically complex system. There is a growing demand for kinesthetic displays in medicine, robotics, and other fields of engineering and scientific research, for training and rehabilitation, sport, games and entertainment. Kinesthetic devices are usually providing information of reflected forces and displacements, though a contact with end-effector does not exclude other components of the haptic sense (the tension in tendons and ligaments, skin stretch and deformations around the joints). This paper overviews the key concepts and the main constraints related to the kinesthetic-based human-computer interaction techniques. Haptic devices have been grouped according to their design features: desktop devices, redundant manipulators and exoskeletons, cable-driven haptic systems, linkage-free force-feedback devices and multifinger displays, and other techniques and devices designed for the specific task. We have tried to present a variety of solutions and to discuss the most common problems revealed and related to the specific design case.

Introduction

To get a true sense and experience about an external world (a perceptual profile of the peripersonal space), people have to possess perceptual knowledge by exploring surrounding objects using the full range of human senses and styles of sensorimotor interaction [24]. For instance, just by pushing an object, people can get a lot of information during a short contact. In particular, afferent signals contain information about the contact surface (stiffness, compliance, elasticity) and properties that can characterize the whole object relying on the previous exploration experience: probable size and weight, inertia, impedance, material, temperature and so on. Sensorimotor interaction with an object can include rubbing, stroking, pressing, squeezing, piercing, and other exploration techniques. By grasping the object, people can assess the shape, size and weight, hardness, compliance, and other mechanical properties and physical characteristics in more detail. However, an absence or reduced exploratory activity impoverishes afferent information [84].

The haptic perception in humans integrates information from sensory modality can be divided in discriminative touch (touch, pressure, and vibration perception), pain and temperature, proprioception (pose and position of the body and limbs) and the kinesthetic sense of movement of body and limbs. A stimulation of haptic receptors can be performed using different types of transducers composed of the mediator of physical signal and actuators of different nature: pneumatic, hydraulic, electro-magnetic, electrostatic, piezoelectric, thermoelectric, and polymeric. With an increasing interest to complex haptic signals for a wide variety of applications (for industrial and consumer use), there is a need for a better understanding of how information can be presented to better fit to the natural processing mechanisms in human haptics.

The first embedded active tactile-kinesthetic (haptic) feedback techniques can be dated to the earlier 60s and what is the most impressive, these devices already had a capability to generate composite tactile-kinesthetic patterns.

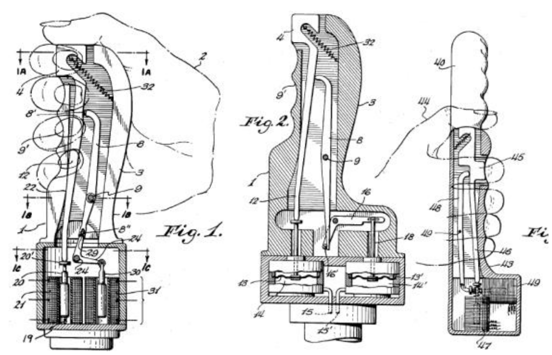

Figure 1. Tactile control indicator [75].

For instance, using several actuators of different type (e.g., solenoid and pneumatic), one of embodiments was able to produce both the displacement and vibration with different magnitudes of the components (feeler) mediating the contact with a human skin (Fig. 1). It is also important that haptic signals delivered to human skin were tightly linked with the parameter(s) being altered and has to be indicated haptically. Such a feedback signal was intuitive and did not require any training to detect and interpret information and changes in the signals delivered to the operator.

Kinesthetic haptic devices can be classified as impedance and admittance devices [28], [114]. Admittance devices are force sensing mechanisms designed using a rigid, often parallel, kinematics. The admittance control implies that initially the user (operator) should apply the force to the manipulandum (or the end effector) anticipating the dis-

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placement of the physical handle or the virtual object by relying on the previous sensorimotor experience. After measuring the input forces, the haptic system will react accordingly with respect to the predefined model. However, high force and precision can be compromised by the low speed and reduced range of deflection angles of the haptic device.

Impedance devices, by contrast, are back-drivable systems that initially sense a displacement of the effector (the physical manipulandum) and then apply appropriate forces and displacements of the virtual objects in response to a shift of the effector linked with a cursor position to provide haptic and visual information to the user.

On the other hand, kinesthetic haptic devices can also be grouped according to their design features: desktop pantographs, exoskeletons, cable-driven haptic systems, linkage-free force-feedback devices and multifinger displays, and devices/systems designed for the specific task. In particular, there is a growing demand for kinesthetic displays in medicine, robotics, and other fields of engineering and scientific research, for training and rehabilitation, sport, games and entertainment.

Kinesthetic devices are usually providing information of reflected forces and displacements, though a contact with effector does not exclude other components of the haptic sense (the tension in tendons and ligaments, skin stretch and deformations around the joints). Generated forces and displacements should be compatible with human capabilities and limits of human perception, that is, force/torque and displacements the user is able to produce himself. The contact interface between human (operator/user) and kinesthetic device can be reconfigured to support different functionalities. Mechanism of kinesthetic device can be actuated by electric motors of different type: DC-motor, EC-motor, Stepper-motor, Piezo-motor, Voice-coil and other actuators translating electrical energy (current) into mechanical energy (force/torque and displacement/rotation of movable components).

Effectors of these devices can be embodied as joystick handles (grips) grasped with two or three fingers, paddles, bars and thimbles or present multiple exoskeletons and mini manipulators [10] providing even more haptic information through the relative position of multiple finger joints. Kinesthetic displays are generally larger and heavier than tactile transducers due to the required higher level of force exerted and displacements of the end effector. Usually, kinesthetic devices are able to produce a maximum continuous force/torque from a few millinewtons to several newtons and tens of newtons.

Desktop kinesthetic devices

A. Pantographs

Pantograph is a planar parallel mechanism (based on parallelograms) that originally was designed to copy and scale diagrams [161] in the seventeenth century. Nowadays, this is a commonly used mechanical linkage for prototyping and development of scientific and engineering applications, industrial and consumer products (Fig. 2). Advanced three-dimensional pantographs have been recently used in design of impedance-type haptic interfaces [18], [30], [108], [119] and neurorehabilitation devices [100], for training in surgery and teleoperation [119].

Figure 2. Images on the top line: Pantograph M1 [150], Pantograph medium [151]. Quanser Serial robot (in the middle) [154]. Images on the bottom line: Quanser 3DOF [106], Quanser 5DOF [107], Twin-Pantograph Haptic Pen [132].

The pantograph is a four-bar mechanism that has the following features which make it advantageous over other mechanical linkages, they are: decoupled kinematics, higher energy efficiency and rigidity, low inertia and a compact size of actuators. In particular, the closed-chain structure of the pantograph provides the high payload-weight ratio. The actuators' placement on the rotating base decreases the linkage inertia. And one of the most attractive features of the pantograph is that forces/torques applied to the manipulandum can deliver to the human operator the high quality kinesthetic and tactile information in real time.

However, artifacts generated by the system (the noise of sensors, the backlash of actuator transmission and others) could have an impact on the resultant forces/torques being transferred to the manipulandum and user's fingers and should be reduced and filtered out even if it will cause some loss of bandwidth. Pantographs have different workspace, force/torque and position resolution (Appendix, Table 1). By providing the force-feedback cues, the pantograph input-output devices translated X-Y (Cartesian) coordinates of the end effector to the joint angle space of linkages, thus, by defining correspondence (mapping) between angular sensor measurements (input) and torque values of actuators (output). Though a non-linearity of geometrical space could be compensated by a calibration procedure, positioning accuracy of the end effector was exclusively relied on the visual feedback.

The collision detection is an important component of the haptic interaction in virtual space. However, simulating interaction through a single point of contact (of the end effector) severally limited the information transfer capability of the haptic channel [125]. The technique itself did not allow to realistically and appropriately distribute and feel multiple forces and torques. This situation has motivated the researchers to integrate different mechanisms providing the kinaesthetic information through bars (links) and joints and tactile stimulation from other kind of transducers affixed to the end effector of the pantographs. The use of the pantograph concept for delivering translational (vertical and horizontal) and rotational force feedbacks during exploration and interaction with primitive virtual objects has laid the foundations for further development of multi-axis manipulators that gradually increased the kinesthetic workspace and parameters of haptic stimuli. But how to achieve the desired trade-off between high performance, accuracy, compact design and greater workspace of haptic controllers with a strong kinaesthetic component?

B. The robot arm like phantoms

The Phantom haptic device has been developed by Massie and Salisbury [88] from the Massachusetts Institute of Technology. Then, Sensable Technologies, Immersion and other companies have designed and manufactured different versions of the Phantom-like devices (Fig. 3). Phantom product line includes 6DOF haptic systems such as Phantom Premium (1.0, 1.5 and 3.0), Phantom Desktop^{TM} (Touch X), Phantom Omni and a series of Virtuose (3D15-25, 6D35-45 and so on).

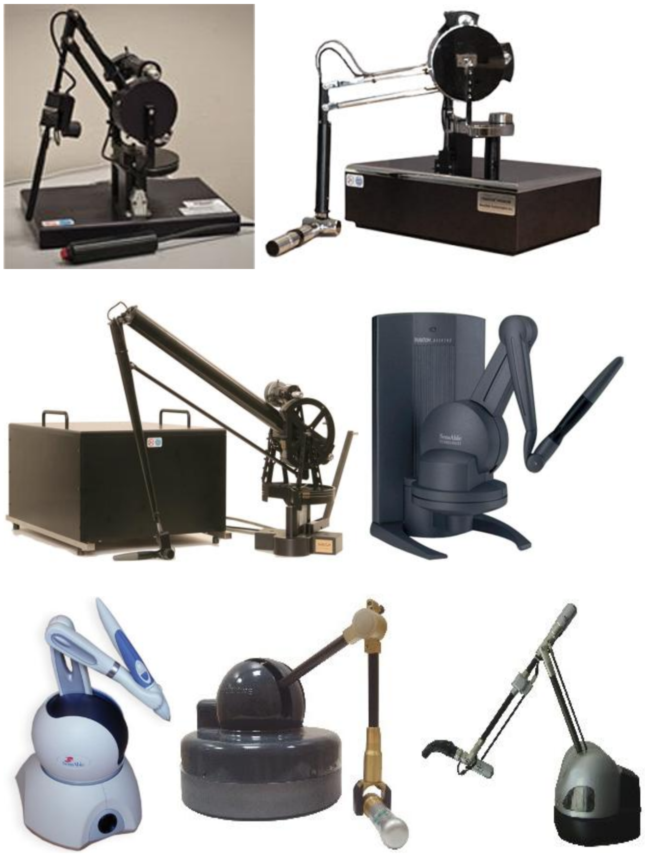

Figure 3. Different versions of the Phantom-like haptic system.

Phantom like haptic devices have been used for simulation training and research in chemistry, biology and medicine, in archaeology and engineering [27] geophysical explorations of deeper geological structures on the seafloor [55] by adding physically tangible sensation to 3D visualization. Force feedback delivered with the Phantom haptic device has enabled a geologist to feel and examine soil density and stratification of different geological formations, and other properties of nature materials [110]. The Phantom system has been used for improving visualization at underwater research of oil and gas exploration [8]. Walker and Salisbury [139] have reported about the navigation in fully immersive virtual geographic environment. Newcomb and Harding [98] have studied visual-haptic-auditory exploration at the road planning in American rural areas. Simonnet [115] has undertaken efforts to train blind sailor for the path planning in open sea in the absence of visual feedback. Stamm [118] and many other researchers [99], [65], [66] have studied recognition and identifying geometric primitives and complex virtual sculptures, 3D objects and scenes in the absence of visual feedback. Special applications have been developed for post stroke rehabilitation and enhanced recovery after surgery [164], for mobile robotic telesurgery [111] and to provide a precise control of robot arms [86], for training in craniofacial surgery [94] and pre-operating planning for total hip replacement [127].

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Gunar Jansson has also explored the volumetric objects, their shape properties, and location in the virtual space in the absence of visual feedback with Phantom Haptic system [64], [65]. The results demonstrated that the haptic exploration does not always lead to a correct recognition of the complex virtual object. In the experiments of Stamm, the participants expressed doubt in their ability to successfully recognize direction and orientation of virtual scenes and virtual rotated objects presented randomly [118]. They could not reveal differences between a cylinder and a frustum of cone, the tip of the explored cone or pyramid, corners of the plane and edges, neither the curvature nor the slope. According to the authors, a haptic force-feedback device with a single point of contact considerably compromises the usability of the haptic device in the shape identification tasks.

The latest model of the SensAble Phantom Omni was the desk-grounded electromechanical haptic device with the active kinesthetic feedback and the workspace of about 160 (width) × 120 (height) × 70 (depth) mm^3. The Phantom Omni had six degrees of freedom for positional sensing (input), but only the first three were actuated by motors defining the position of the end effector on x, y and z-axes (output). The device had removable stylus affixed to the mechanical arm with three more revolute joints. The last three joints provided more flexibility and freedom to operate with the stylus (roll, pitch, yaw) but these joints were not able to alter movements. Therefore, the device was considered as an under actuated robot. That is, while the position and orientation could be manipulated by the user and recorded by multiple sensors, the system was able to generate only three-dimensional vector forces at the specified position. The Phantom Omni device provided continuous forces of 0.88 N and a maximum peak force of about 3.3 N at a good position resolution of about 0.055 mm (Appendix, Table 2).

Despite the diversity of possible applications and use cases, the Phantom Omni device has possessed certain restrictions. According to the Phantom Omni Device Guide [102], it had six degrees of motion provided by six axis points. However, all the degrees of motion had physical limits. When the user felt a physical stop, it could compromise interaction scenario. Stiffness and constancy of the virtual objects was a strict precondition for the haptic feedback acquisition in the experimental environment. Butler also drew attention to a limited range of movement of the device (Phantom Omni) and lack of haptic feedback that was provided for only a single point of contact [15].

Mae Wickham [161] has noted that the drawback to this device was also a lack of torque feedback and three only Cartesian forces, which can be applied to the stylus. While the sensors were easier and cheaper to install than motors [61], by making only three joints being actuated it has led to a limited interactivity of the Phantom Omni. This lack of haptic sensation could confuse the surgeon who should experience natural and intuitive feedbacks during the (robotic-assisted) minimally invasive surgery [44]. Glesser et al. [46] drew attention to the ergonomic concerns of this kinesthetic device. The extensive use of rotations could damage the wrist. During the user study, Ullrich [136] has often observed that some participants tried to increase pressure on the device, when they could not detect any pulse at the palpation during medical simulation in virtual environment. However, a long exploration of virtual objects at a high stiffness has led to overheating of the Phantom Omni and caused limitation of the maximum force generated by the device.

In spite of limitations of the device, the users of the Phantom Omni have noted also the undoubted benefits of it for scientific research such as a clear force feedback, mobility and easy-of-use requiring minimum training. It is important that an exertable force pulling the Phantom Omni stylus was modeled as a virtual spring where the stiffness of the spring could be altered from 0.13N to 2N [117]. Still the Phantom Omni could be adapted for some tasks in surgical simulation training. The appropriate use of tremor filtering could reduce the hand shaking of surgeons [90]. Large changes in the force over small distances, which usually lead to aberrant vibrations (buzzing effect), culd be compensated by adjusting motion scaling. Removable stylus could be replaced by another end-effector suitable for a specific task and application. The Phantom-Omni configuration has appeared to be a powerful tool for understanding afferent information flow and imagery data fusion (e.g., audio-tactile, tactile-kinesthetic) and an experimental assessment of the complex mathematic models [67].

To test novel ideas concerning the kinematics of the robot-like haptic mechanism and cabling system for gravity compensation, Mashayekhi with colleagues [87] have presented the 6DOF haptic device VirSense robot. In contrast to other mechanisms, all powerful gear motors were mounted on the base and the spring system was optimized to reduce the system's effective mass and inertia.

The HapticMaster has been developed by FCS Control Systems [137]. The device has implemented as an admittance-controlled interface having three degrees of freedom in the end-effector, which was operated in a larger workspace with a higher force output and a higher accuracy than any Phantom desktop was able to provide (Appendix, Table 2). Thus, the user exerted a force on the manipulandum and with the admittance control the system generated the appropriate displacement of the end-effector. The HapticMaster kinematic structure has provided the following manipulability: a base rotation, arm up/down displacements, arm in/out extension and exchangeable end-effectors which could be affixed to the end plate of the robot arm for specific applications (Fig. 4). The continuous force exerted was 100 N and the maximum peak force achieved 250N.

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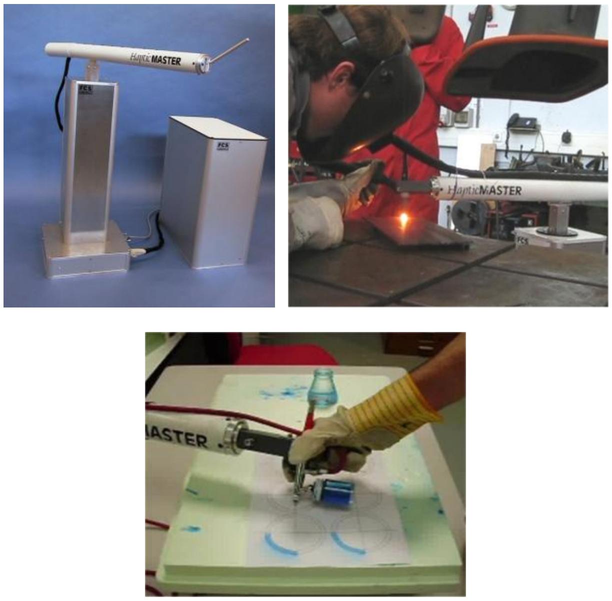

Figure 4. HapticMaster [52] and applications for training different skills [160].

The haptic arm mechanism had a low backlash, while friction in the joints was fully compensated up to the accuracy of the force sensor by the control loop. The HapticMaster device has recorded position, orientation, force and velocity in three dimensions at a sampling rate of up to 1000 Hz.

The Application Programming Interface (API) allowed to program the haptic effects according to the proposed model, such as springs, damping and constant global forces, to generate trajectories of the end-effector, to modify interaction and collision with virtual objects (geometric primitives like cones, spheres and cubes and more complex volumetric objects) in a different way.

Due to its larger workspace and higher force, the HapticMaster have been applied for the vocational training and rehabilitation in mechatronics, electrical and industrial engineering and other areas of specific expertise relevant to practice and service delivery and for scientific research [1], [13], [23], [33], [120].

Redundant Manipulators and Exoskeletons

Different haptic interfaces such as redundant robot manipulators and exoskeletons with kinesthetic feedback have been developed, embodied and applied to various task domains: for training astronauts to the manipulation by a robotic-arm [20], for training fine motor skills in surgery [134], [135] for supervised skills training (to correct the force and velocity) when interacting with a robot, for an exploration of the fusion and integration of the kinesthetic and tactile information in human perception [45] for teleoperation and manipulation in a large operating volumes [11], [133] for post-stroke arm movements and upper limb recovering, and spinal cord injury rehabilitation [49], [97], [101], [116]. Development and use of virtual reality systems in industry demanded human-scale haptic devices, which are still featuring many problems such as stiffness, accuracy, inertia, and bulkiness.

What was the reason to use the robot manipulators and exoskeletons for haptic interaction with virtual environments? The virtual environment is a space the physical properties of which are expected to be fully controlled by the computer system. In practice of course, it is very difficult to create such an environment even with a minimum number of parameters to be controlled.

Figure 5. ViSHaRD10 - Virtual Scenario Haptic Rendering Device with 10 degrees of freedom offered a large workspace [138].

Usually, the virtual workspace is a sector of peripersonal space in front of the user. However, the designers of haptic systems narrowed the task by focusing on the field of the direct contact within a limited space of reach. The field of the contact should exactly be specified within Cartesian coordinates or by other way and then the characteristics of the contact could be altered using the appropriate transducers of energy. This task can be solved with respect to the absolute frame of reference in the space (a desk, ceiling or a base of the manipulator) or regarding the human body.

Modelling the advanced concept of the hyper-redundant haptic display led to development of the ViSHaRD10 (Fig. 5) with kinesthetic feedback for a large workspace and reducing the size of the system [34]. Compared with ViSHaRD6 having a dead space in the centre of the work area due to generic singularities, the ViSHaRD10 has presented a great leap forward. The results of the concept analysis of the 10 actuated DOF Marc-Walter Ueberle demonstrated at International Conference on Intelligent Robots and Systems (IROS) in Japan [134]. The ViSHaRD10 had the largest translational workspace of 1.7 m × 0.6 m and angular workspace with 360 degrees around each axis. Peak force

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approached by ViSHaRD10 was about 170N (Appendix, Table 3).

According to the authors, the kinematic redundancy allowed to eliminate singularities, to achieve higher payload capability for specific end-effectors like drills or scissors in medical applications, to combine tactile and kinesthetic feedback by mounting different tactile stimulators, to study bimanual haptic interaction by avoiding collision and interference between two arms. The self-motion (null space movement) control allowed to maximize inertial performance criteria, to reduce friction forces at the end-effector, and improve acceleration capability.

A mechanical decoupling of the angular and translational movement diminished the dynamics of the orientational DOF and allowed to use actuators having a less torque compared to a human wrist capability. By eliminating the need to perform unnecessary measurements, such a solution also reduced computational effort.

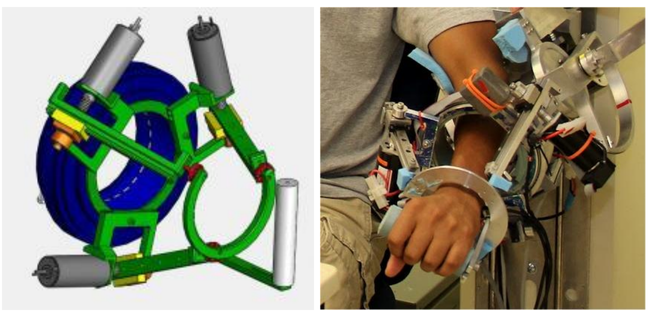


Figure 6. The structure of MAHI exoskeleton for hand wrist rehabilitation [149] (on the left) and MAHI-EXO II [148] (on the right)

To train and precisely control the certain muscles in the virtual environment it was required to develop the wearable kinesthetic devices, though the fact that exoskeletons are firmly affixed to the human body is clearly disadvantageous in terms of ergonomics and safety of use.

The MAHI exoskeleton (Fig. 6, Appendix, Table 3) has been developed in the Mechatronics and Haptic Interfaces Lab at Rice University (Texas) for the rehabilitation after neurological injuries, for training in virtual environments [49]. This haptic arm exoskeleton with five degrees of freedom has provided a kinesthetic feedback to the operator's wrist and forearm. The weight of exoskeleton was more than 4 kg and therefore this device was fixed to the wall to decrease workload and discomfort to the patients who had to wear the device on the arm. The weight of haptic exoskeleton was determined by the use of direct drive mechanism employed to avoid backlash and nonlinearity of transmission. The workspace capability of the MAHI-exoskeleton exceeds significantly the workspace capability of the human arm for some joints and encompasses 90% of the total human forearm workspace. Still a successful rehabilitation was partly achieved due to this feature of the mechanism design.

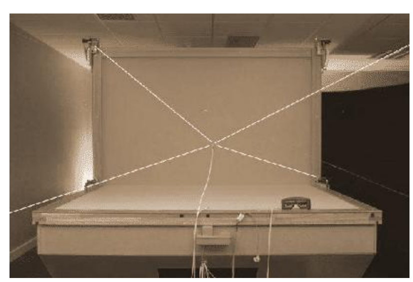
The basic kinematic structure of the 5DOF MAHI exoskeleton (Fig. 6, on the left) was comprised of a revolute joint at the elbow, a revolute joint for forearm rotation, and a 3-revolute-prismatic-spherical (RPS) serial-in-parallel wrist. Thus, the end-effector affixed to the user was mounted on a moving platform connected to the base through spherical joints and three extensible links controllable by linear actuators.

During the training exercises, the axis elbow joint of the exoskeleton was adjusted to align with the operator's elbow joint, and to fit the plate of the wrist of the robot to the plane of the wrist joint of the operator. Such a functionality of the system configuration has preserved natural arm movements by adapting the kinematic structure to the individual human arm joints. The kinematic design has allowed to realize the device with a high structural stiffness, minimum backlash and friction, while having a high backdrivability and a singularity-free workspace. The limited torque output capability of the initial prototype was improved in MAHI-EXO II (Appendix, Table 3).

Cable-driven haptic systems

In 1992 Hirata and Sato proposed the general concept of the string-based haptic display named SPIDAR [59], [85]. Buoguila with co-workers [14] presented the next generation of kinesthetic device with tensioned strings for a large-scale virtual space. The development of cable-driven haptic systems was targeted to deliver the force feedback directly to the point of the contact by reducing inertia, friction and weight of the complex multi-joint linkages.

The force feedback kinesthetic device was called Scaleable-SPIDAR [14] and was intended for use in cave-like virtual environments (Fig. 7). Using tensioned string technique in a large workspace $3 \times 3 \times 3$ m^3, the authors proposed to simulate kinesthetic sensations of the user's hands. The 3DOF SPIDAR experimental prototype consisted of a steel cubic frame with a cave-like space allowing the user to make the large hand movements.



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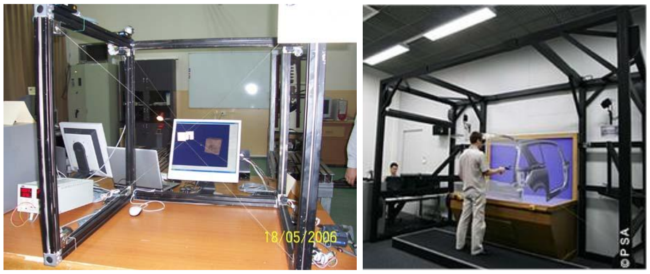

Figure 7. SPIDAR [157] (on the top and on the left) and INCA6D [62] (on the right)

To provide a resultant force in any opposite direction across the workspace it was required to use at least four tensioned strings each of which was controlled with the DC motor, the pulley and encoder affixed to the steel frame. The authors projected the virtual environment on a large screen in front of the user.

The person could explore and manipulate by virtual objects with the help of one or two fingerings worn on the both hands and each supported by four strings. The fingering on middle finger created the force feedback sensation felt as being applied to the whole palm. The user was able to feel the weight/gravity, the contact force feedback and inertia of virtual objects.

The position resolution of Scaleable-SPIDAR was about 15 mm, the force sensation changed in all directions from a minimum of 0.005N to a maximum of 30N (Appendix, Table 4). According to the authors, the force feedback provided a considerably increased performance in manipulation and interaction with virtual objects in the game environment. However, the navigation task was slow. The main limitations of the experimental Scaleable-SPIDAR were unreeling and entangling of strings, and the accuracy of hand position detection that was dependent on a movement velocity of the user's hands. [31] has explored limitations of a parallel cable-driven kinesthetic device INCA6D for human-scale virtual environment, see Appendix, Table 4.

Yang and Zhang [166], [167] introduced an own concept of the compact planar cable-driven haptic device (CDHD) for rendering kinesthetic and tactile effects in the virtual environment (Appendix, Table 4). The cable-driven mechanism was able to provide two-dimensional translations and a one-dimensional rotation around the Z-axis perpendicular to the base plate by delivering kinesthetic sensations, while the tactile display (a piezoceramic plate) was affixed to the end-effector generated tactile stimuli. The workspace was bordered with a frame of 350×350 mm^2 that could be optimized individually. The gear motors of active modules have been attached outside and below the supporting plate. A location of driving modules provided a safe and reliable exploration of the device. The maximum retraction force that could be applied through cable-driven mechanism was about 14N.

According to the authors, the device could provide the users with reliable kinesthetic sense of retraction, collision and tilting. However, this type of haptic controllers cannot provide a repulsive force in the direction opposite to the base plate (along Z-axis).


Figure 8. An elastic force-feedback on a Pocket PC [50].

The scaleable haptic devices with tensioned cables have been created and used for interaction with cave-like virtual environments [59], [31] and other haptically-augmented games and simulations. On the other hand, an intention to apply kinesthetic and force-feedback on mobile devices and to interact with virtual environment less dependent on the absolute frame of reference (such as a frame, a base, a desktop) motivated game designers to find a suitable solution for wearable haptic systems.

Hachet and Kulik [50] have studied an elastic 2D force feedback with a pen input on a personal digital assistant (PDA). Their experiments demonstrated that with an elastic force feedback added to input movements with the pen, continuous navigation tasks can be completed faster, more accurately and more efficiently than in the absence of such a feedback (Fig. 8).

Besides the hyper-redundant haptic displays, some haptic devices with partly reduced physical parameters such as a workspace, dimensionality and generated forces have been able to demonstrate a greater communication efficiency and practical impact on applications that are less dependent even on visual information. For example, CyARM (Cyber Arm) have been developed for a space exploration relying on kinesthetic and tactile cues mapped onto an egocentric reference frame within a peripersonal space. The concept and the prototype design are shown in Fig. 9. The distance detector could be of any technology (laser, ultrasonic), but the problem that the researchers were trying to solve was related to the kinesthetic imagery of relative distances, to the cognitive and sensorimotor distance coding (see e.g., [26]).

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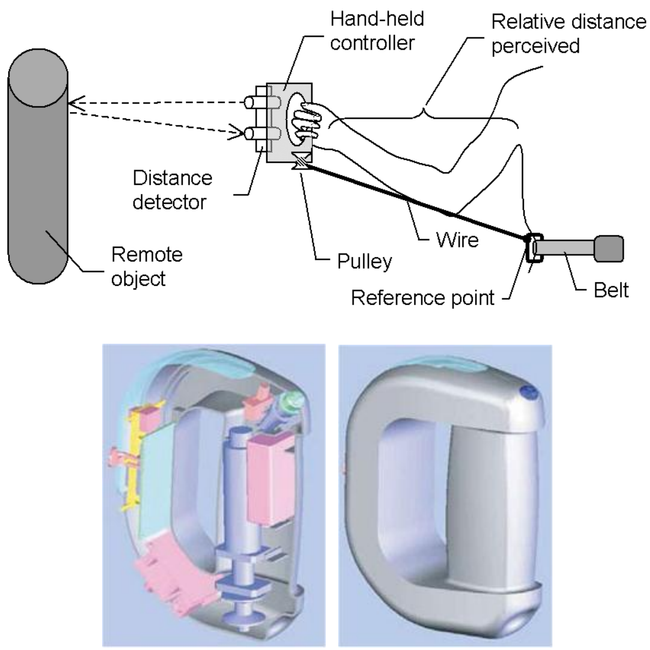

Figure 9. The CyARM's concept and the prototype design [156].

Still usually, the kinesthetic imagination in a peripersonal space relies on human experience. Therefore, when such an experience have been gained in the visual environment, in the absence of visual feedback the kinesthetic imagery cannot rely on the stored in memory the template of an egocentric reference frame. On the other hand, in a case of the congenitally blind person having a normal hearing, the kinesthetic imagery has been developed in the sound environment (if so). In such a case, a spatial sound experience should be coordinated with a remote and peripersonal haptic perception. That is, blind person cannot immediately rely on egocentric frame of reference.

Nevertheless, due to training-induced brain plasticity, the blind subjects demonstrated high judgment accuracy (more than 90%) of detecting not only stationary but also by tracking the moving objects, a space between several objects and even their shape (with sharp edges) by proving communication efficiency and usability of the haptic imaging technique [63], [3], [94]. By holding CyARM and exploring the peripersonal space the user was able to collect three-dimensional haptic information projected onto the egocentric reference frame. In particular, the strength of the wire tension to the point of reference was proportional to measurable distance to any object in the direction pointed by the hand. The tight wire tension indicated the short distances to the objects that could be reached by bending the arm. The tension-free wire signified that the object was out of reach. In accordance with hand movement and distance to target, the controller supported the wire rewinding with a maximum speed of 1.0 m/s.

At a size of 15×10×3 cm^3 the weight of the CyARM was about of 0.5 kg. Ultrasonic frequency of 38 kHz provided distance detection in a range of 0.3-3.0 m updating information every 50 ms (Appendix, Table 4). However, the weight of the device and continuous holding an extended hand in air to explore the space can be considered as a serious disadvantage [19].

Investigating the virtual arc of the circle Chinello and Prattichizzo with co-workers [25], [105], used the portable wearable tactile display (Fig. 10, on the left). This haptic display had three actuated degrees of freedom of the parallel mechanism and reproduced normal and tangential components of the contact force at the fingertip. Though the device did not generate forces applied to the hand, kinesthetic sensations (of perceptual haptics) were accompanied with the tactile feedback. The portable tactile display consisted of two parts: the static part was affixed to the back side of the index finger using three miniature DC planetary gear motors and the mobile part (end effector) was in contact with the fingertip.

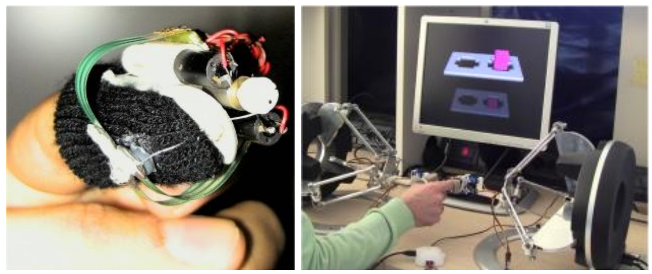

Figure 10. 3DOF wearable tactile display [153] (on the left) and two tactile displays being attached to the OMEGA-3 [100] (on the right).

Mobile platform was able to move by modifying the strain of the three wires attached to DC motors affecting the position and orientation of the end effector. Using this display on the finger, the person could explore different heights of the curvature of the virtual surfaces and reveal the differences between them. The virtual sphere/arc was generated and moved under the finger from starting point to end point creating illusion of the contact with a virtual shape (convex or concave). The researchers analyzed the relationship between the forces recorded at the fingertip and the platform's orientation (platform tilts according to the curvature of the virtual surface) and displacement. The step of the curvature height was 10 mm per trial at a constant distance of the arc length of 30 cm. The authors reported that the percentage of correct answers for each curvature discrimination task passed the Shapiro-Wilk normality test by varying from 55 to 95%. Thus, the authors have concluded that 3DOF tactile display could extend functionality of other haptic systems, as shown in Fig. 10 (on the right). In particular, the Omega-3 (Appendix, Table 2) was used in later research [105]. It was also supposed that the wearable tactile display (see more specifications in Appendix, Table 4) could be used in different applications for rehabilitation tasks, for simulation-based robotic surgery and entertainment.

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It is known that the sense of gravity involves various components of haptic perception: the proprioception, the cutaneous and kinesthetic senses in the arm in estimating the weight of the grasped objects. Minamizawa with co-workers [92] developed the prototype of the tactile-kinesthetic system for gravity simulation and an evaluation of the weight recognition (Fig. 11). For experimental setup, the researchers combined the finger-worn haptic display (Appendix, Table 4) to supply multipoint tactile feedback and the OMEGA-3 (Appendix, Table 2) haptic device to provide the kinesthetic feedback to the point of gravity. Information related to the virtual contact between fingers and the object was conveyed with the help of the tactile display modules affixed to the fingers. The OMEGA-3 haptic device simulated the weight and inertia of the virtual object. Four virtual weights from 100 to 400 grams were presented with the kinesthetic device and tactile display for 1 second of time under four experimental conditions: by applying kinesthetic feedback on the palm, wrist, and forearm, and by applying no kinesthetic feedback. The weight recognition was poor in two cases: at the use of only kinesthetic feedback and the minimum weight, and at the use of only tactile feedback and the maximum weight. The combination of the kinesthetic feedback applied to the arm and tactile feedback to the fingers demonstrated a high accuracy of recognition for each of four values of the simulated weight.

By using two devices, Minamizawa with colleagues were able to separate cutaneous and kinesthetic components of haptic sensation delivered to the fingers and to the arm respectively. The experimental system proposed by the authors showed the high accuracy of the gravity simulation.

According to other researchers (e.g., [104]), Minamizawa's findings can be used for recording the force distribution among fingers in the hand grasping tasks for rehabilitation, in telepresence and teleoperation scenarios, for gentle manipulation by virtual nano-materials. Abovementioned the OMEGA-3 haptic device used in the research of Minamizawa [92] and Prattichizzo [105] belong to the well-known and commercially available Phantom-family haptic devices (Appendix, Table 2). Despite of the workspace limitation to about 0.0022 m³, the OMEGA-3 device enabled the high resolution of displacements and rendering high contact forces.

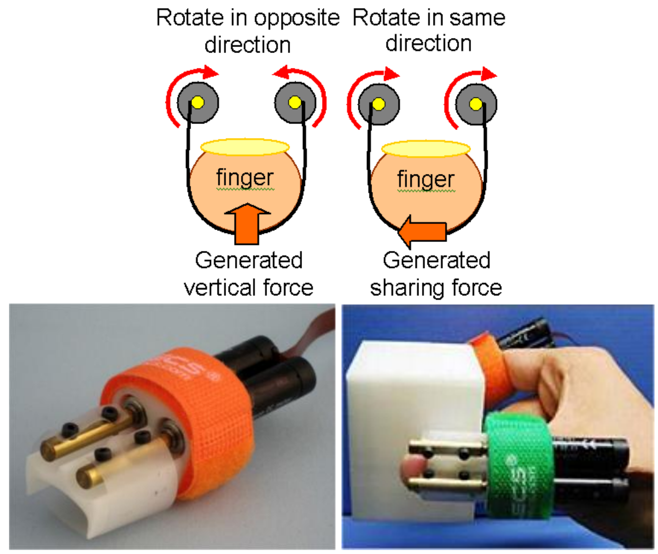

Figure 11. Wearable haptic display [147].

As can be seen from the previous section, cable-driven haptic devices require to be in continuous contact with the user's hand. Moreover, cables should not interfere, to be twisted, pulled or tensioned by restricting the user's movements. While cables can only pull and not to push, there is a need for redundancy to generate forces in opposite directions. Due to the inherent elasticity of the cable, haptic system cannot simulate a very hard contact as a linkage-based system does. A cable tension is not a constant for any joint-angle and the system has to be individually calibrated. Would it be possible to realize a linkage-free haptic feedback with respect to the kinesthetic component?

Linkage-free force-feedback devices

Together with colleagues, Barbieri has developed the method for non-visual exploration of mathematic graphs and images relying on audio and haptic output [9]. The blind users experimented with the transducer of multimodal stimuli - the vibrating pen "AudioTact" that presented a combination of the digitizer pen and vibrating motor (Fig. 12 on the left, Appendix, Table 5). Being connected with a touch screen or a graphic tablet (e.g., Aiptek or Wacom), this device has allowed to the user to get auxiliary information linked with the specific regions of the surface explored with a digital pen/stylus. The relative position of the hands delivered to the user a kinesthetic component that together with audio and vibration signals allowed to easier navigate over the surface, to explore and mentally reconstruct a spatial arrangement of the specific regions and related content.

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Figure 12. Vibrating pen AudioTact [142] (on the top) and Vibrating pen with a stopped rotor [158] (on the bottom).

The spatially distributed information can be referred to geographic, historical or statistical data as well as other linked values, attributes and attitudes. The technique could be further enhanced with a specific exploration strategy and tactile information presented as different raised textured patterns. However, even if this concept relied on a perceptual kinesthetic component, it did not produce any externally controllable kinesthetic feedbacks.

The concept of eccentric-rotating-mass vibration or vibrating the motor with a stopped rotor [113] (Fig. 12 in the middle and on the right) complementing a digital pen was a good starting point for mobile and linkage-free haptic devices. Still, the haptic transducers of such a configuration were constrained by a limited number of parameters that could be effectively controlled. Many efforts have been undertaken later to extend a functionality of eccentric-mass vibrators by controlling the rotating mass (e.g., [112]).

Studying subtle effects of the length and heaviness perception (see, e.g., [29], [76], [165]) has led to the development of more sophisticated haptic actuators. Ungrounded force-feedback devices, which have been implemented and studied in different laboratories, have demonstrated that a dynamic control of displacement-torque characteristics could potentially increase information transfer rate for data representation than the use of conditional vibration “messages” [126].

For example, the TorqueBAR (Fig. 13, on the left) have been designed as ungrounded linkage-free haptic device integrated a physical interface, input/output controller and software [122]. The system (see also Appendix, Table 5) has been used for studying dynamic interactions based on kinesthetic inertial feedback. A physical interface presented a two-handled bar with one degree of freedom and a movable center-of-mass that created moments of force exerted on the handles via displacements of the DC servo motor, having a mass of 0.25 kg, along the steel rods.

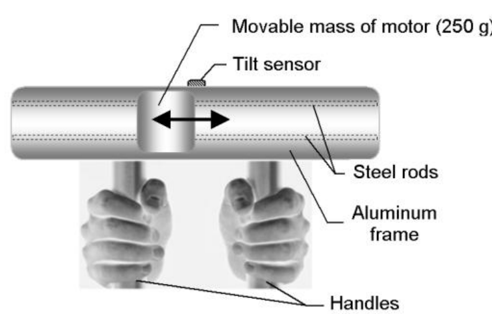
The center-of-mass position has been dynamically altered according to the value of the tilt sensor when the user inclined the bar. The weight of the entire device was about 1 kg. The length of the TorqueBAR was 0.48 m at a width of 0.11 m. An accuracy of motor positioning was 0.13 mm.

In the experiments on balancing the virtual ball, relying on haptic feedback only, the subjects demonstrated 75% worse accuracy than in the presence of graphical feedback and they complained of fatigue. However, with a trajectory-matching task the subjects were better able to react on a dynamic change of the moment of force caused by displacements of the center-of-mass than when they were sensing an absolute value of this moment of force.

Moreover, Amemiya et al. [6] have noted that the TorqueBAR did not produce a pulling sensation. Instead, the displacements of the center-of-mass produced a weak rotation moment on an axis parallel to the ground. Such a configuration of haptic transducer would also be hard to produce moments of the force feedback in two other dimensions. Hemmert et al. [58] emphasized that besides a limited dimensionality, the gravity-based haptic devices also had a low expressivity. Nevertheless, the authors were optimistic regarding the possible application of the TorqueBAR that could warn the user about obstacles.

Then, Tomohiro Amemiya has developed the concept of eccentric-mass-rotation by applying dynamically altered asymmetric acceleration of a movable mass. He focused on designing the wearable haptic navigation assistant (Fig. 13 on the right) and displaying navigation-specific information [5], [7].

The force-feedback device Buru-Navi exploited the nonlinearity of human haptic perception. As humans better feel pulses than harmonic oscillations, rapid acceleration of mass displacements produced a strong and clear sense of the local signal, and what was more important, people could easily and accurately detect a vector of the force moment when acceleration was significantly different in opposite directions.



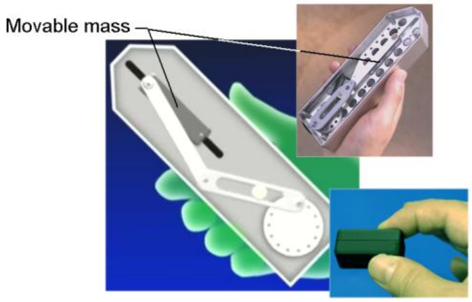
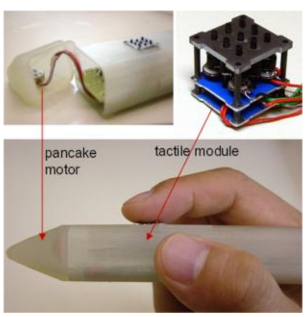


Figure 13. The TorqueBAR concept (on the top) and Buru-Navi handheld force feedback device (on the bottom) [143].

Probably the authors will continue to make improvements by adding new functionality to the prototype, as they are aiming to miniaturize and integrate this concept of the haptic transducer into commercially viable products (Fig. 13 on the right).

Other ungrounded pen-shaped devices, which have been developed by Kyung [79]-[83], Withana [163] and Kamuro [69], have delivered kinesthetic information beyond the limited workspace of the linkage-based haptic devices. The pen-shaped devices allowed to feel the features of virtual objects in mid-air, of large objects in simulation environments and on the large surfaces [68], [69]. In particular, Kyung and Lee [79], [81] have conducted a series of experiments with the pen-like haptic device Ubi-Pen (Fig. 14, on the left) generating an extended set of the haptic effects during interaction with a touch screen of the tablet PC.

In the earlier prototypes, an embedded tactile module generated different haptic effects such as patterns of vibration and textures, and distributed pressure under the fingertip has been used. Each pin was actuated by TULA35 [131] ultrasonic linear motor providing an average speed of 8mm/s, though the travel distance of the pins was limited to 1 mm. The distance between neighboring pins was 3 mm. This miniature module had a size of 12×12×12 mm^3 and weight of 2.5 grams. The bandwidth (a refreshment rate) of the tactile display was 20 Hz. In addition, the vibrating motor was used to control three levels of the pins' vibration intensities (0, 2, and 5 Hz) while tactile information was presented by the pin matrix tactile display.



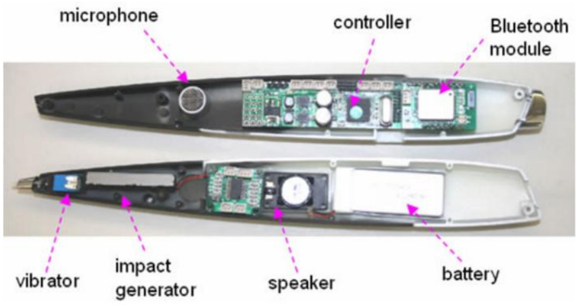


Figure 14. UbiPen [77] (on the top) and wUbiPen [156] (on the bottom).

The UbiPen had a length of 12 cm and a weight of 15 grams though initially the controller was not embedded into the pen.

The later versions [81] of the wUbiPen were equipped with more powerful vibration actuators (eccentric motor and piezoelectric linear vibrator of AAC Acoustic Technologies), embedded microcontroller and battery (Fig 14, on the right). The authors intended to use the haptic pen for imaging different textures, as a simulation device for medical palpation, as a mobile communication device supporting a symbolic secure communication, as a learning tool for interactive drawing by children and visually impaired people. The specifications for UbiPen device are presented in Appendix, Table 5. While the UbiPen was able to display Braille symbols, both pens could be used for interacting with mobile devices for simulating surface gratings, raised patterns of dots, roughness and other haptic effects.

Due to self-perception of the finger joint-angle positions, any person could get kinesthetic sensations from a spatial configuration of the fingers [123]. Kamuro et all. [69] presented the concept of the ungrounded pen-shaped kinesthetic display (Fig. 15) that was able to deliver multidimensional forces to the fingers. This haptic device allowed to feel seven levels of the force with a maximum of 4.9 N when the user explored the features of 3D virtual objects in mid-air without movement restrictions.

The pen-shaped device consisted of two parts: a base of the device affixed to the user hand with the ring as a reference point in order to generate the reaction force, and a grip part holding with three fingers (Fig. 15, on the left). The grip-part was movable with respect to the base toward-backward and away from the central axis (leftward-rightward), providing the forces on the fingers (Fig. 15, in the middle).

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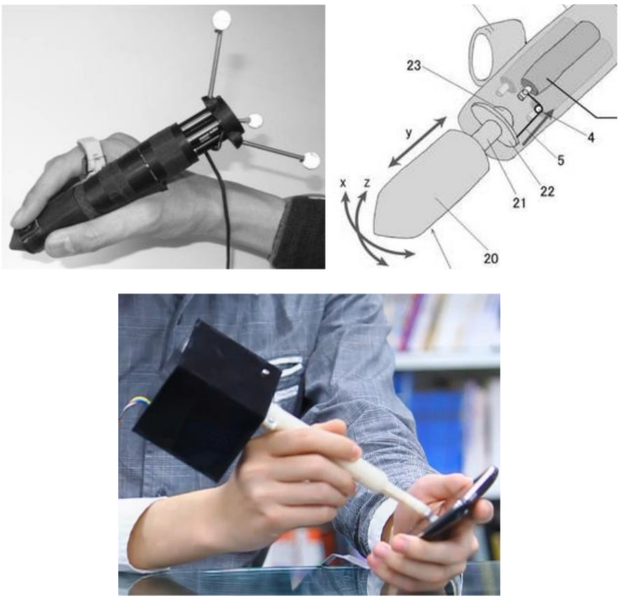

Figure 15. Ungrounded kinesthetic pen-shaped display [152] (on the top) and immersive haptic stylus [159] (on the bottom).

Three geared DC motors embedded into the base part of the device controlled all the movements between two parts of the pen. When the grip was shifted parallel to the central axis of the pen, the user was able to sense "pushing" or "pecking" the virtual objects. When the grip was moved away from the central axis these movements generated the sense of friction or touching an object.

In 2010 Withana with colleagues [163] have presented the new immersive haptic force feedback stylus "ImpAct" (Fig. 15, on the right) developed for the surface computing, and the results of technical evaluation. The authors also discussed possible interaction scenarios of the device functionality and revealed limitations. This pen-shaped device was consisted of two parts: a solid cylindrical shaft, which was able to move inside the hollow external grip with the use of the geared DC motor attached to the solid shaft for generating kinesthetic sensations and force feedback. The relative motion of the shaft with respect to the grip has lead to changing the stylus length when the user has pushed the stylus against the screen. The solid shaft has shrunk by becoming virtually shorter. The users were able to observe the virtual end of the stylus when the virtual counterpart of stylus immersed into the digital space for interaction with virtual objects behind the screen.

However, the actuation functionality of the ImpAct stylus was limited to a single dimension only and the capability of emitting the forces only from the surface and not towards the surface. Only the tip was considered as a haptic-sensitive area and forces have been simulated only when they interfered with the tip of the virtual stylus. Other limitations were related to the low displacement accuracy of about 3 mm (6%), and the bulkiness of the prototype, as a weigh of the control module affixed to the stylus was 0.243 kg. The high weight had a negative impact on usability of the stylus and manipulating virtual objects.

Nevertheless, six-dimensional tracking the position and rotation of the stylus (along x, y, and z axes, yaw, pitch, and roll) via accelerometer and magnetometer allowed to perform an exploration of spherical objects, plane surfaces, their edges and a variety of features of the virtual objects in game scenarios and other applications. For instance, the researchers have experimented with a billiards game, mobile games for iPhone, simulated the sense of heartbeat of virtual animals (frog and horse). A support of 3D CAD drawings and medical applications make the concept of the ImpAct as a promising approach for designing mobile haptic interfaces.

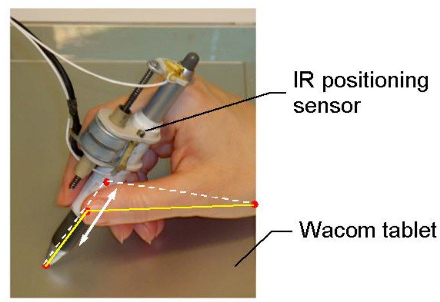

Figure 16. The StickGrip linkage-free haptic device.

The StickGrip linkage-free haptic device (Fig. 16) has been designed and implemented at the University of Tampere, Finland [35]. The StickGrip presented a motorized grip, a kind of exoskeleton, for the Wacom pen input device and it was intended for haptic visualization and interaction with scalar data, which could be applicable to the 3D cases when interactions occur at planar surfaces.

The point of grasp of the penholder was sliding up and down the shaft of the Wacom pen so that as the user explored the virtual surface by means of the pen, s/he could feel that the hand being displaced towards and away from the physical surface of the Wacom pen tablet. The weight of the StickGrip haptic device was comprised of 13 g of the pen and 30 g of the exoskeleton. The use of the Portescap linear stepper motor (20DAM40D2B-L) did not require any additional gears, and led to low noise and equal torque with no differences in directionality of the grip displacements that might confuse the user. The StickGrip has a range of 40 mm (±20 mm) of the grip displacements with an accuracy of ±0.8 mm for the Wacom pen having a length of 140mm. The grip displacements with an average speed of about 25 mm/s of the point of grasp in this range provided an accurate kinesthetic sense of distance (closer and further) and direction regarding the physical surface of interaction (the pen tablet) and self-perception of the finger joint-angle positions [123].

Consequently, such a feedback was a part of the afferent information regarding the heterogeneity of the data presented, for example, as brightness or color gradient of the virtual

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surface. The functionality of the StickGrip device was not only related to the scalar data imaging, but also to modifying the values (input) proportionally to the distance between the point of grasp and the pen tip. The workspace during the surface exploration was only limited by the size of the pen tablet.

The StickGrip haptic device was tested for enhanced haptic visualization and interaction with different types of data in the presence and absence of visual feedback. In particular, haptic visualization of geographic maps was reported in [37], [40], visualization of bathymetric information have been studied in [41]. An impact of the haptic sense for interpretation of ambiguous images was addressed in [42]. An investigation of the virtual curvature, volumetric shapes and sectioning concept in the absence of visual feedback was studied and discussed in [36], [39]. Manipulating the tabular data has been presented in [38].

However, the use of the induction-type Wacom pen has not allowed the authors to employ a magnetic flux linkage to provide a stronger attraction force in the prototype described.

Romano and Kuchenbecker [109] developed a portable haptic device the AirWand to increase the usable haptic workspace and kinesthetic information (Fig. 17).

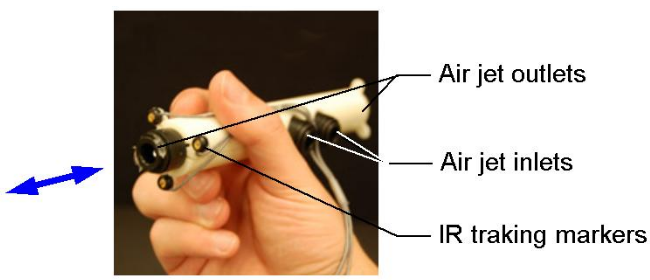

Figure 17. Linkage-free AirWand kinesthetic device [140].

The AirWand kinesthetic device having only one degree of freedom (1DOF) was able to deliver kinesthetic information within of about $15m^3$ of the workspace, while many of commercially available haptic systems had the workspace limited to $0.006\ m^3$ or so. To determine the position and orientation of the handheld device the researchers used IR optical tracking (Optotrack). The AirWand had two air jets creating forces in the positive and the negative Z direction lengthwise the longitudinal axis. The design of this kinesthetic device allowed to make rotations around the X and Y-axis at an angle of about 170 degrees and any rotations around Z-axis. A reservoir with a significant volume of pressurized air was connected to AirWand with a long flexible tube. The compressor was capable to continuously supply $0.00127\ m^3/s$ of air flow at a pressure of 620 kPa. That corresponds to a mass of 0.0092 kg/s producing the maximum continuous output force of about 3N or short pulses of 7.58 N. These reflective forces were even greater than would be required in practice but a little underpowered for a larger workspace that could satisfy different tasks in the VR experiments.

The tip of the tool was displayed as a small ball acting as the pointer in the virtual environment. The user was able to interact with virtual surfaces of different stiffness controlled by the software. Still, air valves installed at the beginning of the long flexible tubes have led to a dead volume to be pressurized to achieve the needed force. Thus, due to the lack of pneumatics the force could be achieved with delay of about 400 ms. Nevertheless, even though air jet pulses have produced loud sounds, it is important to note the advantages of such the technique. The portability and low mass (70g) of the manipulandum (AirWand) allowed to enable linkage-free kinesthetic interaction in a larger workspace and has led to a low inertia of haptic system. The forces created by air jets have dominated over an acoustic noise side effect.

However, even in a case of the perfect design, an air jet-based haptic device is not able to simulate very hard wall contacts. The effects were felt even springier then with a cable-driven system. Still according to the authors, the AirWand kinesthetic tool could be applied for training and evaluation of sensorimotor skills, for patient rehabilitation, teleoperation and entertainment [121], [129], [130].

Multifinger haptic displays

Among many attempts in designing the multifinger haptic display, to be historically correct we should probably refer to the earlier work of Cadoz and Florens [16] who carried out the research since 1978. It is obvious to an expert, that any keyboard of music instruments is the source of the force applied to each finger. Moreover, the musicians are able to distinguish thin differences in the force, which needed to be applied to the key in dependence on the exact finger location and many other factors. The Retroactive Gestural Transducers (RGT) have been designed to apply force feedback to actual multifinger gestures during interaction with virtual objects (Fig. 18), such as perceived weight or rigidity, in the same manner as during interaction with marionettes [17].

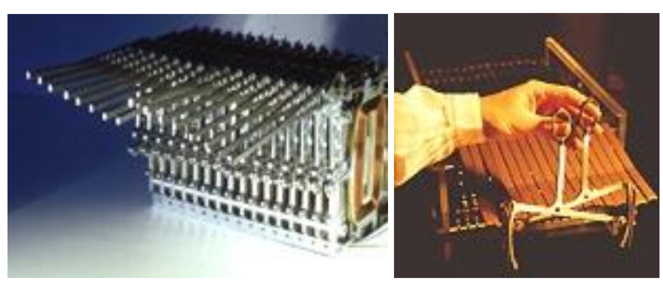

Figure 18. The module of 16 slice-motors (clavier-petit on the left) and the way of getting the different number of degrees of freedom (on the right) [141] using special linkages - habilages.

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The authors have developed the universal 1D force module that could be assembled into the block of a minimum 3 or more than 88 units (Appendix, Table 6) and the special linkages to fingers a kind of the mechanical transmission component – "habillage" (a joystick-like linkage fixed to each finger). These linkages have been used to convert the rectilinear and parallel displacements of the self-sensing actuators and force feedback into the manipulated object features. However, this desktop device caused more problems than the concept and idea itself. Unnatural hand position and dexterous manipulations as well as artistic skills from software designer did not allow to compete with other solutions (see more in Appendix, Table 6).

If it is not a special case for prosthesis/rehabilitation, a suit for diver, pilot/astronaut or other vocational needs, people reject to wear gloves or anything that should be affixed to the hand. The problem is that the surface of palm (glabrous skin) is about 2-2.5% of the whole body surface. It is densely packed with vascular structures of relatively large diameter and plays a significant role in heat exchange [48], having a strong impact on haptic perception. Therefore, we will not attempt to review here any haptic gloves and exoskeletons, which have different mechanical design of actuators and sensors assembly but almost similar disadvantages related to ergonomics and usability. Still let us overview a couple more multifinger haptic devices different from the affixed to the fingers exoskeletons [43] and gloves.

After extensive research undertaken by Tan [124], [125], Casiez with co-workers [21] also attempted to develop the information-rich haptic signals. Using three degrees of freedom decoupling they have developed the ground-based multi-finger force feedback device DigiHaptic (Fig. 19). Being embodied as the Logitech SpaceMouse, the DigiHaptic provided effective force feedback and diminished user's hand fatigue.

The authors have presented the technical principles and possible applications for a given device configuration and modes of operation. Three levers of this device were activated by three DC motors and were in a contact with the thumb, forefinger and ring finger. Using thumb finger the person was able to move virtual objects along the X-axis (screen width), with the ring finger s/he could move objects lengthwise the Y-axis (screen height) and the objects control along the Z-axis (depth) was assigned to the forefinger.

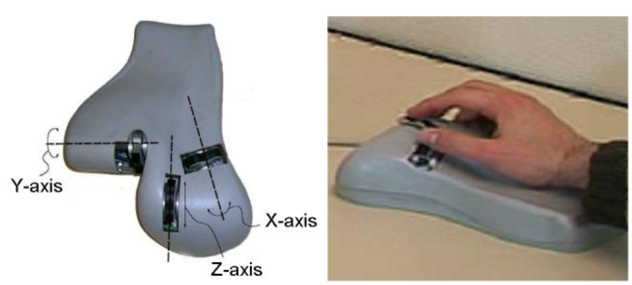

Figure 19. DigiHaptic - ground-based multi-finger force feedback device [143].

The user was able to manipulate virtual objects with the help of the levers at the same time or sequentially by translating and rotating them. Each lever has one degree of freedom with a range of ±60 deg. and 20 mm of the rotation radius (Appendix, Table 6). This angle was considered as an optimal value for the lever manipulation. According to the authors, maximum force of 2N was appropriate for creating the stiffness limiting movements of the user fingers.

This haptic device was used either in an isotonic mode, by changing spatial coordinates proportionally to the lever displacement, or in an isometric mode, by changing spatial coordinates proportionally to the force generated by motors and applied to the levers according to the spring stiffness model. The virtual space operating in the isotonic mode was limited to a cube with an edge length of 10 cm. In the isometric mode, simulated springs always pushed the levers back to a neutral position at equal distances from the lever boundaries. Though the virtual spring stiffness could be configured to be close to an elastic mode, non-linearly and inversely to the lever displacements or in any other way, the main problem was the unnatural input and interaction technique requiring time for sensory-motor relearning.

Five fingers of one human hand could be placed not only inside (exoskeleton-like) but also opposite to the hand of other human or robotic arm. Such a solution – five-fingered haptic interface HIRO-II has been developed and embodied at the Gifu University (Japan) by Prof. Kawasaki with colleagues [73]. This haptic interface (Fig. 20, on the right) was designed to deliver the kinesthetic and tactile information at the five fingertips of the human hand in motion.

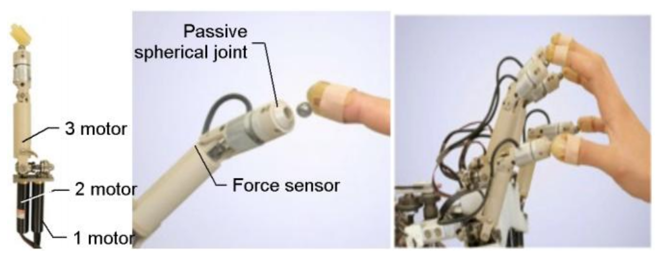

Figure 20. Haptic finger and assembly of the 5 fingered haptic interface HIRO-II [145].

The authors supposed that the multifinger haptic interface could mimic the human upper limb (Fig. 20, on the right). Consequently, the kinematic structure has been designed to have the 6DOF arm and 15DOF hand to follow the operator's hand being in a direct contact with the fingertips using passive spherical permanent magnet joints (Fig. 20, in the middle). To display the virtual contact, joints of the fingers mechanism were force controlled simultaneously. Three motors (Fig. 20, on the left), having three joints and allowing 3 degrees of freedom, actuated each finger. The first joint of

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the finger was connected to the base to realize abduction/adduction functionality. The second and third joints allowed flexion and extension. The workspace of the thumb and other fingers was 535 mm^3 and 713 mm^3 respectively. In all joints DC servomotors with geared transmissions and rotary encoders have been used. The permanent magnet of each finger holder had the attraction force of 5N. The six-joint haptic arm provided six degrees of freedom in the workspace of 400×800×300 mm^3. The redundant force and position control provided the maximum manipulability of the haptic interface. However, what is the most important feature that has been realized in the project was that at any moment the user was able to decouple his fingers from the robot arm.

The average force error of the initial prototype (HIRO) was 0.2N. This error was decreased to 0.08N in the second version of the haptic interface (HIRO-II). To demonstrate an applicability of the multifinger haptic system the authors have created the future science encyclopedia. The software application demonstrated the three virtual words: astronomy, the history of ancient creatures and the micro world. Later, the authors have developed the medical application of the multifinger haptic system for training palpation skills [4], minimal-invasive surgery [32], post-stroke rehabilitation [60] and for teleoperation of the anthropomorphic robot arm [72].

Nevertheless, this device was heavy enough (the weight of the arm and hand was about 6.9 kg and 0.73 kg respectively), grounded to the base (a table) and suffered of the robot arm singularities, static friction in the joints and backlash. Moreover, the users still felt a light depression due to a strong connection to the robot arm.

Other kinesthetic-based interaction techniques and devices

By adding kinesthetic feedback to computer input devices, many researchers have modified the regular mouse and joystick input devices [12], [71], [74], [80], [127]. The developers assumed that an extended mouse functionality in the graphic environment would be the most popular and usable concept in the human-computer interaction, in engineering and architecture, in applications for robotics and factory automation, for training hand dexterity and vocational skills, as a powerful tool for CAD systems, drawing and entertainment, art and sound synthesis and so forth.

For improving the PC accessibility for blind and visually impaired people, Biagiotti with co-workers have designed and evaluated the 2DOF mouse with tactile and kinesthetic feedback [12]. The goal of the research was optimizing the kinesthetic-tactile feedback for imaging geometric shapes and contours. The experimental mouse was affixed to the Cartesian structure manipulator designed with the use of only two linear motors (P01 23×80), having a high stiffness without gears and backlash. Due to such a design, the mouse system was able to follow even very fast hand movements, though the length of the slider has limited to the workspace of 110×110 mm^2. Using this force-feedback mouse, the visually impaired subjects were able to track straight lines, continuous curved lines (circle) and polygonal shapes (square). In particular, during the free-space exploration the person used the force of 0.5N. When the user had to track a line, the mouse constrained hand movements to retain pointer over a virtual path, so that the person could analyze the path and recognize the perimeter of the virtual shape. According to the authors, the recognition accuracy of the shape and shape elements was high enough (Appendix, Table 7). The authors proposed to apply the force-feedback mouse for navigation in the absence of visual feedback by tracking the predefined paths. However, the major drawback of the solution was the type of actuator that continuously consumed a lot of power.

Simplicity and portability of another device concept presented by Chang [22] have originally been discussed by Akamatsu and Sato [2] and has meaningful advantages over the initial pin-based embodiment. Chang with colleagues extended an approach for developing haptic media through closing the interaction loop between kinesthetic input and output. The researchers developed the Formchaser device to reduce the cognitive complexity at an exploration of different textures on the map (including a small text and contour/grid lines). This haptic device was the single-point finger-held mechanism indicating the line thickness and giving a quick form (profiling) of the digital texture. In response to alterations of the physical attributes, the Formchaser was able to raise the finger over light-colored mountains and sink it into the depth of dark-colored valleys. Moreover, it was possible to add dynamic features to the static content to feel, for instance, the waves and ripples moving across a water surface. Thus, an exploration of the flat features was enhanced by the kinesthetic component in the direction normal to the surface that provides imaging information beyond the bounds of two dimensions in an intuitive way (see also [89]).

Gourishankar et al [47] has developed the high fidelity haptic device – HapStick that mediated physical input into the virtual game environment through the manipulation by a tangible object as a billiard cue (Fig. 21).

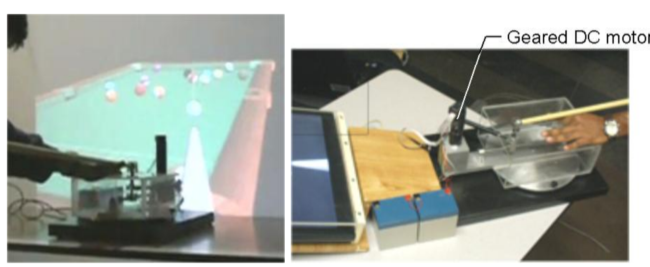

Figure 21. A high fidelity haptic device for tangible interaction in virtual game environment [145].

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The proposed configuration of the tangible interface provided 3DOF motions (pitch, yaw, and translation) of the manipulandum (the cue stick) supported with a perceptual kinaesthetic feedback, though only translation movements (a single dimension) have been enhanced with a controllable haptic feedback by restricting the movement along the axis to simulate cue-ball collision at the end of the stroke with a peak impact force of 4.32N. The manipulandum has been allowed to move freely (apparent mass at cue tip was about 100 g) under the time varying force until the haptic wall has been reached. Then a constant force was applied by pressing the device against the haptic wall. To produce a force feedback a geared brushless DC Maxon motor was used (a maximum continuous torque was about 6 Nm) along the linear degree of motion. The cue stick motions have been recognized with an accuracy of 0.05 mm using the optical encoder of the DC motor rotation and three-axial accelerometer affixed to the tip of the cue stick with a peak acceleration of 5 g (Appendix, Table 7).

Like other experimental kinesthetic devices, the HapStick demonstrated its advantages and shortcomings. According to Hammond [54], this haptic device provided highly accurate measurements of applied forces, but did not take into account spin effects as well as angular velocity of the billiard ball. According to the authors, the angular velocity of the cue ball, which plays an important role in advanced spin and jump shot techniques, has been considered to be zero.

The HapStick interface combined virtual billiard game with a tangible interaction complementing the game with a strong haptic feedback (see also [95]). However, both in the billiard game with the HapStick device and in the virtual ping pong game [78] players behavior has been limited to a restricted area of the game space [91] which was impractical for gamers.

Conclusion

In this overview, we have tried to focus on the kinesthetic haptic devices, but it is impossible to ignore the tactile and proprioceptive components that always accompanying any human activity (the tension in tendons and ligaments, skin stretch and deformations around the joints). It was demonstrated a variety of solutions able to deliver haptic information through forces and torques in a specific location of the workspace to stimulate human body. It is possible to control reaction forces with respect to different reference frames using a very complex mechanical system of linkages and linkage-free autonomous inertia-based force/torque transducers. It has recently been realized that the level of “usefulness” of low DOF devices can actually be higher than intuition would predict, with the benefit of a great deal of design simplicity and efficiency. The combination of several low DOF devices can even lead to a richer set of metaphors. Nevertheless, redundant manipulators and multifinger haptic systems are still required for industrial applications, for significantly larger workspaces and for studying novel interaction concepts for advanced human-machine interfaces. The redundant systems could help to study and solve the problems concerning the large linkage structures (backlash, singularity, apparent inertia, stiffness of the whole system) will stimulate designers to apply novel smart materials and technologies (flexible fiber batteries, electro-active polymers (EAP) as artificial muscles and so on).

As technology advances, new challenges arise, requiring non-traditional innovative approaches for visualization as a way of (sensitization), by converting different data types into a human perceivable form. Novel visualization techniques extend inherent human perceptual abilities to provide access to non-perceivable properties of the physical world and the virtual one. Modern interactive systems give the user the great flexibility in the mapping of data onto perceptual dimensions (visual, auditory, haptic, and even olfactory and gustatory). The great flexibility, however, can easily give rise to visualization that do not adequately represent the data structure and their relationships, which can be considered false, inaccurate or misleading.

In particular, any perceptual workspace (visual, auditory, haptic) of human is nonlinear. Therefore, designing an appropriate visualization technique for haptic information is of great challenge. However, the distribution of force vectors across the haptic workspace could not be easily embodied and normalized with respect to the personal sensitivity, as the haptic sense affected by many factors. Therefore, the mechanical models of the force feedback simulation always suffered from many assumptions and limitations.

Fortunately, some physical properties of objects and materials such as compression/extension of spring, inertia, friction, roughness and rigid collisions could be simulated through only tuning the mechanical impedance and magnitude of the end effector deviation near the point of the virtual contact. Rendering the haptic events such as collisions with deformable and multiple real-life objects will lead to increasingly complex models of the system behavior. To study more complex interaction tasks it is required to develop more complex haptic transducers, controllers and drivers.

Since the “coarse” haptic signals were often used as auxiliary information to complement the vision-based human-computer interaction, the nonlinearity of the haptic workspace has never been considered as an essential factor of the primitive haptic feedback. However, haptic information is not always a feedback. In daily life, mental images linked to human activity are also associated with feelings accompanying muscle sensations and coordination. Motor imagery, in turn, involves the generation of an action plan that is grounded on previous experience and accompanying feelings (tactile, kinesthetic, proprioceptive). That is, the motor

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imagery is able to stimulate haptic imagery for creating the mental model of anticipated perceptual information. That is, haptic perception can precede action by providing feedforward functionality.

The virtual haptic space presents an extremely complex system of properties, qualities and parameters of the physical world being translated into the haptic events and their relationships with the content, which may not be perceived by other modalities. When it would be possible to achieve compliance between perceptual expectations/experience and afferent information, we could conclude that haptic information is presented seamless and could be processed (perceived and interpreted) intuitively. Thus, the most important conclusion that can be drawn from this overview is that the major problem in designing the artificial haptic space is still the degree of anticipation and consistency between simulated haptic information and haptic imagination of the person that has been developed through years of experience and the formation of cross-modal associations.

Appendix

Table 1. Pantographs

Name: type, (Ref.)	DOW	DOF/T	Max/cont. force or torque, N/Nm	DOM and/or resolution
M1 [56], [57], [168]	2D 100×60 mm^2	2D	2 N	10mm
Mk-II [18]	2D 160×100 mm^2	2D	10 N	~100 um
Quanser serial robot http://www.quanser.com/products/2dof_serial_flexible_link	2D 508×508×225 mm^3 Axis1 ± 90 deg. Axis2 ± 90 deg.	2D	T_{axis1} 8.6 Nm T_{axis2} 1.7 Nm	Sensor: rad/count Axis1 1.534 × 10^{-5} Axis2 1.918 × 10^{-5}
Quanser twin http://en.souvr.com/product/200812/1652.html	3D x ± 135 mm y -75-165 mm z infinite deg.	3D	Fx 10.1/3.1 Fy 7.5/2.3 Tz 252/77Nmm	Sensor: counts/rev 20,000
Quanser http://www.quanser.com/products/5dof_wand	5D X ±240 mm Y 85 to 335 mm Z -215 to +235 mm Roll ± 85 deg. Pitch ± 65 deg.	5D	F_x 7.7/2.3 F_y 7.0/2.1 F_z 9.0/3.0 T_x 750/230Nmm T_y 810/250Nmm	Sensor: counts/rev 20,000
Twin-Pantograph Haptic Pen [119]	5D X ±60 mm Y ±37.5 mm Z ±37.5 mm Roll ± 45 deg. Yaw ± 45 deg.	5D	F_x 48/5 F_y 21/3.3 F_z 40/4.1 T_x 324/34Ncm T_y 396/41Ncm	X 22mN Y 45mN Z 23mN Roll 0.19Ncm Yaw 0.18Ncm

Table 2: Desktop kinesthetic devices (specifications provided by the manufacturers)

Name: type, (Ref.)	DOW	DOF/T	DOM and/or resolution	Advantages	Disadvantages
SensAble Phantom Omni: desk-grounded stylus-type device with kinesthetic active force feedback on the x, y, z axes. Datasheet	6D 160W×120H ×70D mm^3 (~0.0013m^3)	3D Provided hand movements pivoting at wrist, by holding the stylus. 3D translational actuated axes and 3D rotations.	X,Y,Z, yaw, pitch, rall Measurings: pos. resolut. 0.055mm rotation angles with ±5% linearity. Max/cont. exertable force 3.3N/0.88N inertia at tip 45g; backdrive friction 0.26N	Portable design, cost-effective model. Solid virtual objects feel stiff. Removable stylus. OpenHaptics SDK is available	Only 3 actuated forces, 1 point of interaction. Physical limit of DOF; the surgeon doesn't feels the patient due to lack of haptic feedback; longer durations of exploration with high stiffness

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					causes overheating of the device.
Sensable Phantom Premium 1.0: desk-grounded stylus-type device with kinesthetic active force feedback on the x, y, z axes.	3D 254W×178H ×127D mm^3	3D Provided hand movements pivoting at wrist, by holding the stylus. 3D translational actuated axes and 3D rotations (optionl).	X,Y,Z, (yaw, pitch, rall opt.) Measurings: pos. resolut. 0.03 mm Max/cont. exertable force 8.5N/1.4N inertia at tip 75g; backdrive friction 0.04N	Larger workspace. OpenHaptics SDK is available	Only 3 actuated forces, 1 point of interaction. Physical limit of DOF. Limited control stiffness due to the low physical damping present in the joints.
Sensable Phantom Premium 1.5HF: desk-grounded stylus-type device with kinesthetic active force feedback on the x, y, z axes.	3D 381W×267H ×191D mm^3	3D Provided lower arm movements pivoting at elbow with the stylus. 3D translational actuated axes and 3D rotations (optional).	X,Y,Z, (yaw, pitch, rall opt.) Measurings: pos. resolut. 0.007 mm Max/cont. exertable force 37.5N/6.2N inertia at tip 150g; backdrive friction 0.2N	Larger workspace. High force feedback. OpenHaptics SDK is available	Only 3 actuated forces, 1 point of interaction. Physical limit of DOF. Limited control stiffness due to the low physical damping present in the joints.
Sensable Phantom Premium 3.0: desk-grounded stylus-type device with kinesthetic active force feedback on the x-y-z axes.	3D 838W×584H ×406D mm^3	3D Provided full arm movements pivoting at shoulder with the stylus. 3D translational actuated axes and 3D rotations (optional).	X,Y,Z, (yaw, pitch, rall opt.) Measurings: pos. resolut. 0.02 mm Max/cont. exertable force 22N/3N inertia at tip 159g; backdrive friction 0.2N	Largest workspace. OpenHaptics SDK is available	Only 3 actuated forces, 1 point of interaction. Physical limit of DOF. Limited control stiffness due to the low physical damping present in the joints.
HapticMaster: Ground-mounted admittance-controlled device with robot arm, which was operated in a large workspace with a high force output and a high accuracy [137]	3D 400×400×400 mm^3	3D Provided human hand (wrist) movements via end-effector of the robot arm. 2 translational actuated axes and 1 rotational actuated axis.	The kinematic chain from the bottom up yields: base rotation, arm up/down, arm in/out. Force sensor in the end effector. Measurings: pos. resolut. 0.004 mm Force resolut. 0.01N Max/cont. exertable force 250N/100N Min .inertia at tip 2kg Max velocity 1m/s	Mechanism was build for zero backslash, for hard surface simulations; exchangeable end effectors can be affixed for appropriate industrial and scientific apps. FCS HapticAPI and OpenGL compatible.	Friction is hard to avoid mechanically; don't able to simulate very stiff virtual objects; simulation of free air motions is hard; Poor ergonomics of the robot arm and high inertia caused usability problems.
Virtuose 6D: Desk-grounded 6D admittance-controlled device had a large workspace and high forces,	6D 1300W×1080 H×653D mm^3 workspace corresponding to movements of human	6D Provided human hand (wrist) movements via modular end-effector (gripper or handle) of the	Measurings: pos. resolut. 0.006 mm Max/cont. exertable force 31N/8.5N Max/cont. rotation torque 3.1Nm/1Nm	Static compensat. of the device's own weight. Multi-platform SDK(API) is available	The main limitations were the increased inertia and friction compared to other devices. This required a force feedforward loop for

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enabling interact with CAD's digital models. Datasheet	arm.	robot arm. 3 translational & 3 rotational actuated axes.	inertia at tip 220g		more transparency, associated with greater complexity and drift.
OMEGA-3: desk-grounded 3D active force feedback device designed for high mechanical stiffness apps. http://www.forcedimension.com see also Omega and Sigma series [100]	3D $\varnothing 160\times 110$ mm^3 ($\sim 0.0022m^3$)	3D Provided force feedback via end-effector to human hand (palm, wrist and forearm). 3D translational actuated axes.	X,Y,Z Measurings: pos. resolut. <0.01 mm Max exert. force 12N	-delta-based parallel kinematics -active gravity compensation -automatic driftless -velocity monitoring -electromagnetic damping -enables rendering of crisp contact forces. Multi-platform haptic/robotic SDK are available	Provides only translational actuated axes and no rotational capabilities.

Table 3: Manipulators and Exoskeletons

Name: type, (Ref.)	DOW	DOF/T	DOM and/or resolution	Advantages	Disadvantages
ViSHaRD10: Admittance-controlled hyper redundant robot arm with 10 actuated DOF [133]	Cylinder of $\varnothing 1.7m\times 0.6m$	10D Provided forces at fingers, wrist, elbow and shoulder. 10 translational and 10 rotational actuated axes.	X,Y,Z, yaw, pitch, rall Each rotation 360 deg., translational velocity >1m/s Max force 170N Accuracy F_x , F_y 50mN, F_z 100 mN Tyaw, pitch 13Nm Trall 4.8Nm	A larger workspace free of singularities, high force capability, avoidance of user interference, self-motion control, mechan. decoupling the angular and translational DOF.	Bulkiness, the reduction of overall stiffness of the system.
MAHI Exo I: Exoskeleton that comprised of a revolute joint at the elbow, a revolute joint for forearm rotation, and a 3-revolute-prismatic-spherical (RPS) serial-in-parallel wrist. [49], [101]	5D 90% of the human forearm workspace, except for limitation in the flexion of the elbow joint	5D Provided 5 rotational (RPS) actuated joints via robot that encompasses hand	deg/torque, Nm Elbow: flex./ext. 90/5.5; Forearm: pron./sup. 180/5.1; Wrist: flex./ext. 85/2.9; Wrist: add/abd. 85/3.4	Alignment of the rotation axis of human joints and device joints, the biggest manipulability in the centre of the wrist workspace, minimal backlash and friction, high structural stiffness, absence of singularity in the robot workspace.	Big weight to be supported by the operator; limited torque output capability, low manipulability outside the center of workspace for each joints, a lack of gravity compens., the torque output limitations of the 3-RPS wrist platform
MAHI Exo II: Elbow, forearm and wrist exoskeleton [101]	5D More than 90% of the human forearm workspace, except	5D Provided 5 rotational (RPS) actuated joints via robot that encompasses	deg/torque, Nm Elbow: flex./ext. >90/11.6; Forearm:	Additional improvements: reduction of backlash and singularities, increased torque output in some degrees of freedom,	Big weight to be supported by the operator; Still, there are workspace limitations of the parallel wrist

	for limitation in the flexion of the elbow joint	hand	pron./sup >180/2.3 Wrist: flex./ext. 72/1.67; Wrist: add/abd. 72/1.93	improved wearability allowing the device to be abducted at the shoulder, and streamlined interchange between left and right arm configurations.	design.

Table 4: Cable-driven haptic systems

Name: type, (Ref.)	DOW	DOF/T	DOM and/or resolution	Advantages	Disadvantages
Scaleable-SPIDAR: Space Interface Device for Artificial Reality [14], [31], [59]	3D 3×3×3 m^3	3D To simulate sensations, associated with weight, contact and inertia, to both hands (two fingerings) within a cave-like space. Provides 3D translations using the resultant force of tension from strings to fingerings.	X,Y,Z Force range: 0.005N-30N Pos. accuracy <15mm Intertia – 50gF	Ability to display different aspects of force feedback and kinesthetic sensations within different size cave-like space without visual disturbance.	Still bulky serving two fingerings only. The strings may interfere with each other (an operator tries to turn around or cross deeply his hands); the apparent winding radius can be altered, or an operator quickly moves hands that makes the string no longer straight – these conditions can cause a position miscalculation. When power is switched on, overlapping loops tend to slip back, causing sharp blows of cables.
INCA-6D haptic device, specifically designed for work in VR environments. Based on SPIDAR of Prof. Sato www.haption.com/site/pdf/Datasheet_Inca.pdf	6D 3×3×3 m^3	6D Provides rotation & displacements of the hand holding the gripping tool. Provides 3D translations and 3D rotations using the resultant force of tension from strings to the gripping tool.	X,Y,Z, yaw, pitch, rall Max force/cont 37.5N /12.5N Max torq/cont. 5Nm/1,5Nm Gripping tool has proximity sensor, resolut. in position 0.2mm, but rotations are limited to ±40º.	It has a large workspace and high forces, enables a scale one interaction with digital models coming from CAD. Winding and unreeling problems were solved. SDK (API) is available for the major operating systems.	Still bulky serving two hands only. The workspace in rotation is rather small, and depends on the geometry of the end-effector. Gripping tool rotations are limited to ±40º. It can be enlarged to some 30°, but at the cost of translation workspace, which then will be reduced.
CDHD: cable-driven	2D+1D 350×350mm^2	2D+1D provide 2D	X,Y,abduction -adduction	CDHD has a simple universal mechanism &	Each cable could not generate ac-

planar haptic device with kinesthetic and tactile feedback [166], [167]		force feedback and 1D torque feedback on the plane.	Max force - 14.2N, torque – 1901Nmm, X-Y position accuracy 0.13mm	configuration, which is singularity-free. Workspace was individually adjusted.	tive repulsion force and even provide same forces in opposite directions.
CyARM: Translated a distance to an object at 0.3 – 3 m to the length of tensioned string affixed between the belt and tool. [63], [94]	1D 81-810 mm	1D Provided force feedback to the hand via restriction of extension arm movements regarding to the user body (belt).	Ultrasonic dist. detector The coefficient of the wire length against the measured distance to the object was set to 0.27.	Low cost, portable interface for navigation in the total absence of visual feedback. Cyber Arm allowed to sense the distance to the nearest obstacle through body sense of the extended hand length.	Continuous scan peripersonal space by holding an extended hand in air with 500 grams controller that caused fatigue, by impairing the system usability. A poor perception of objects having smooth edges.
3DOF cable-driven nail-mounted wearable tactile display. [25],[104],[105]	3D	3D A mobile platform actuated/tilted modifying the strain of the three wires according to the virtual curvature.	Yaw, pitch & roll angles of mobile platform regarding the fixed frame. Max force - 1.5N at 30 deg. inclination, 0.3N for each cable, accuracy (step) 0.05N	Portability and extended (3D) capabilities of the nail-mounted easy tactile display for imaging the surface curvatures. Manipulations are capable in mid-air or it can be affixed to a desktop haptic device (e.g., Phantom - like).	Rise time delay was ~100ms to reach the reference value at accuracy of 2%. Vert. displacements of the mobile platform were limited to 3 levels. Fixing mechanism can impact on a fingerpad sensitivity
Finger-worn wearable haptic display for gravity (weight) and interia simulation [92], [93]	1D Manipulations in mid-air stimulating fingerpad	1D+1D vertical stress/ deformation and sharing stress on fingerpads makes a sense of weight	Four virtual weights from 100 to 400 g Max sharing stress 1.4 at accuracy 0.2 mN/mm^2	The finger-worn haptic display was able to supply multipoint tactile feedback in the absence of proprioceptive sense. It can be affixed to other haptic devices (Phantom/Omega).	Approach has been tested only in the static grasping condition. Performance of the virtual weight recognition was lesser than 50% for weights >200g.

Table 5: Linkage-free force-feedback devices.

Name: type, (Ref.)	DOW	DOF/T	DOM and/or resolution	Advantages	Disadvantages
AudioTact: digitizer pen with vibrating motor, sound and speech feedbacks	2D $200\times150mm^2$ Manipulations with respect to the surface	1D Vibration torque provided to the fingers holding the pen of digitazer and	X-Y– 3048/2032 lpi Pressure (opt) – 512/1024 levels (Wacom)	Direct interaction with graphical images in the absence of visual feedback through sound and vibrations accompanying by speech cues regarding	3 discrete levels of vibration signals: weak/great/max. Workspace is limited to the tablet or touchscreen.

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[9]	of graphic tablet	sounds of 0.3-3 kHz		the user activity and the data pointed out.	Neither reflective nor attractive force-feedback.
TorqueBAR: two-handled bar with a movable center-of-mass [122]	3D Manipulations in mid-air.	1D Displacements of the center of mass of 1kg with a movable mass of 0.25kg Force moments exerted on the handles.	Tilt sensor – 0.13 mm	Ungrounded system can be used for studying sense of balance (gravitation) and dynamic interactions based on kinesthetic inertial feedback.	- Produced a weak rotation moment instead of pulling sensation - Heavy mass of 1kg device caused fatigue. - Low expressivity
Ubi-Pen: pen with tactile 3×3 pin array [83]	3D Manipulations in mid-air	Provided to skin: trust force 980mN or <196mN per pin	Pin elevation – 1mm Pin-to-pin gap – 3 mm	Portable ungrounded easy pen (15 grams with external controller). Can display vibration, Braille symbols and patterns of roughness or textured elements. Ubi-Pen can be affixed to other haptic devices (e.g., Phantom -like).	Low-density pin-display (TULA module) can cause confusion and inconveniences. Unwanted sounds of actuators.
wUbi-Pen I & wUbi-Pen II: pen with eccentr. motor, piezo linear vibrator, mike, speaker, or/and 3×3 pin display [81]	3D Manipulations in mid-air	Provided to skin: trust force 980mN or <196mN per pin other specs N/A	Pin elevation – 1mm Pin-to-pin gap – 3 mm other specs N/A	Portable ungrounded easy pen with embedded controller. Can display vibration, impact, Braille symbols (opt.) distributed pressure and sounds. Pen can be affixed to other haptic devices (e.g., Phantom -like).	Limited capabilities of the TULA module. Unwanted sounds of actuators.
Kinesthetic pen-shaped display [68], [69], [70]	3D Manipulations in mid-air	3D displacements of the finger joint-angle position with a maximum force of 4.9N and vibrations	3D Force-feedbck 0-3.2N, step 0.4N 3D position detection and tracking with accuracy of 1mm by IR camera; Mike used for scanning objects and materials.	User was able to -sense pushing or pecking the virtual objects; -interactively explore and create/copy haptic content (texture) from real to virtual word; - several devices can work simultaneously without interferences.	-Weight of 70g with external controller & wired connection was a little heavy. -20 ms delay arose from frictions in the mechanism. -Special grasp (holding fixture) was required due to individual differences in perceived force. -Unable to generate an attractive force to a virtual surface.
ImpAct: immersive haptic force feedback stylus for the surface computing	6D Manipulations with respect to the touch or screen sensitive	1D Provided displacements of the hand holding the stylus grip towards and back-	6D Measurings: - stylus length - position & orientation (yaw, pitch, and	Tracking the position and rotation of the stylus with respect to the surface of interaction allowed to perform an exploration of complex	-ImpAct was not able to interpret forces perpendicular to the axis of actuation. -Unable to generate an attractive force to a

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[163]	surface	wards regarding the surface of interaction.	roll) with accuracy <2%. Max reflective force 10.8N Min grip's displacements - 3 mm or 6% of accuracy.	relief surfaces and volumetric objects, to simulate a variety of features of the virtual objects from the viewpoint of direct touch behind the screen surface.	virtual surface. -Residual friction (3.58N) and torques have been neglected. -Bulkiness and heaviness (0.243kg) of the prototype.
StickGrip: exoskeleton of the Wacom pen [35], [36], [39]	3D 208×150mm^2 Manipulations with respect to the touch sensitive surface of the graphic tablet.	1D Provided displacements of the hand holding the stylus grip towards and backwards regarding the surface of interaction.	X,Y,Z -2032 lpi Pressure – 512/1024 levels (Wacom) Measurings: - grip position regarding the tip (IR-sensor) Accuracy ±2% Max reflective force 15N Grip displacem. Min ±0.8 mm Max ±20 mm	- Low noise (no gears); - Equal torque in both directions; - Low weight (43g with external controller). - Accurate feedback about the distance and spatial relations (surface profile) - Pressure sensor allowed to simulate a "passive" attractive force. - Provided the capability to actively modify the virtual surface.	- StickGrip was not able to interpret forces that are perpendicular to the axis of actuation. -Did not provide inclination measurings. - An average speed of 25 mm/s of the grip displacements limited a simulation of the fast alterations of the data.
AirWand: an impedance-type handheld haptic device [109]	6D 15m^3 Manipulations in mid-air	1D Two air jets created axial forces to the hand holding AirWand in the positive and negative Z-direction	X,Y,Z, yaw, pitch, rall Handling tool rotations are limited to 170º. Resolution of IR tracking <0.9mm Max continuous output force was about 3N or pulses 7.58N Accuracy of force feedback - 0.137N	The portability and low mass (70g) of manipulandum, a low inertia. The tool could be applied for training and evaluation of sensorimotor skills, for rehabilitation, teleoperation and entertainment.	- Air-based manipulations generate a strong acoustic noise. - the max continuous force and the pulse mode actuation had a limited time to provide a stable force-feedbck. Due to the lack of pneumatics design the max force could be achieved with 400 ms delay. The system did not prevent the IR-markers' occlusion.

Table 6: Multifinger haptic displays

Name: type, (Ref.)	DOW	DOF/T	DOM and/or resolution	Advantages	Disadvantages
RGT: Retroactive Gestural Transducers A self-sensing actuator slice was composed of a linear actuator and abs. position	3-88 axes 30 mm/axis Min distance between two points of manipulation 13.8mm	1D×N axes A clavier-like keyboard provided force and displacement through "habillage" – a joystick-like	Min 3 self-sensing actuators per block. Measurings: Position. res. 2um Force res. 1.3 mN Max translation force - 80 N	Allows to apply real gestures to virtual objects (images, sounds, virtual 3D objects), to feed tactile sensations back to the fingers, such as perceived weight or rigid-	A limited workspace with unnatural hand position. Weight of 600 g per slice (axis or finger) plus controller and power unit was high enough.

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electromagnetic sensor with a plunging con-tact-less core. [16], [17]		linkage fixed to each finger, can form 2D, 3D, 6D etc. arrays of force-feedback joysticks.	Max cont. force 40N Response 0.2 ms Resid friction 5mN Max speed 1.8m/s	ity of simulated ob-jects. It is possible to as-semble any number of 1D-keys into array according to the num-ber of DOFs required. It is recommended for manual dexterity train-ing.	Dexterous manipula-tions limited a gen-eral use of the device as linkages to fingers were inconvenient and might interfere with each other. Poor ergonomics and usability.
DigiHaptic: ground-based multi-finger 3D-decoupled force-feedback haptic mouse. [21]	3D 3 levers, rotation of each 120 deg	3D Provides 3 rota-tional actuated levers at thumb, index and ring fingers	Rotational levers Measurings: Resolution 0.06deg of levers' rotation Max force 2N	Supported both isoton-ic and non-tiring iso-metric modes in a compact design. Cali-bration is not required. A low(10ms) response time.	Training period is a precondition for dexterous manipula-tion by decoupled DOFs and with virtual objects.
HIRO-II: Five-fingered robot arm cou-pled via finger-tips to the hu-man hand [53]	15D (Hand with 5 fing.) 3D-Finger workspace of thumb 713cm^3 workspace of finger 535cm^3 6D (arm): Shoulder 2D Elbow 1D Forearm 1D 400×800×300 mm^3	6D+15D Provided forces to the human fingertips via easy coupled /decoupled hold-ers (caps).	Fingers: Max force 3.5N Force error 0.08N Velocity 0.23m/s Torques 1/2/3 joints: 0.8/0.4/0.2 Nm Arm: Max force 45N Max torque 2.6Nm Transl. vel. 0.4m/s Rotational vel.1.4 rad/s	Force and tactile feelings in hand fingertips, large work-space, simulated pre-cisely the human hand movements, using the correct collision detec-tion algorithm.	Bulkiness, unneces-sary static friction at the joints and back-lash, large weight, low hardware stiff-ness leaded to haptic arm vibration, de-creasing the haptic arm manipulability near kinematicly singular points, device was grounded.

Table 7: Other kinesthetic-based devices.

Name: type, (Ref.)	DOW	DOF/T	DOM and/or resolution	Advantages	Disadvantages
Force-feedback mouse [12]	2D 110×100mm^2	2D Provided forces to the hand through fingers holding mouse	Measurings: Max/cont. force 33N/9N accuracy 0.5N Max velocity 2.4 m/s Pos. resol. 1um	Simple mechanical design with very high stiffness (242N/mm) and without backlash; 2 linear motors with-out gears, backdrivable with high speed and high resolu-tion. Force controller com-pensated the static friction and other undesirable dynamic phenomena.	Very high power consumption was required cont. (72 VDC, 4 A); Mechan-ical design was bulky. Device can be used only being stationary grounded. In the stopped posi-tion both motors will consume about 8A.
Formchaser: A single-point finger-held mechanism.	3D A tabletop space	1D Provided forces to a single finger and perceptual kinesthetic sense	X, Y, Z Measurings ac-cording to servo-motor HS55: Force N/A	Simple mechanical design. A close inter-action loop between kinesthetic (perceptu-al) 2D input (X,Y) and	Very low efficiency of the motor used. Slow response time due to a high gear ratio. Limited work-

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[22]		to the hand holding/moving device (like a mouse)	Max/cont. torque 0.13/0.11 Nm Operat. Angle 40° Speed 170ms/60°-140ms/60° (at no load)	1D output (Z) (instrumental). Reduced the cognitive complexity at an exploration of different textures.	load and functionality. Instrumental kinesthetic input cannot be performed
HapStick: Haptic cue for billiard game's simulation [47]	3D 2 rotational 1-translational active axis 50.8mm	1D Provided forces of cue-ball collision in the hand holding the cue/stick	Y, yaw, pitch Measurings: Impact force 4.32N Res. Friction 0.1N Inertia 100g Pos. resol. 0.05mm	Device mediated physical input into the virtual game environment. Provided highly accurate measurements of applied forces.	Still, did not take into account spin effects as well as angular velocity of the billiard ball.

References

[1] S. Adamovich, G.G. Fluet, A.S. Merians, A. Mathai, and Q. Qiu, "Incorporating haptic effects into three-dimensional virtual environments to train the hemiparetic upper extremity," IEEE Transactions on neural systems and rehabilitation engineering, Vol. 17, No 5, pp. 512–520, October 2009.

[2] M. Akamatsu, and S. Sato, "Mouse-type interface device with tactile and force display: Multi-modal integrative mouse," The 2nd Int. Conference on Artificial Reality and Tele-Existence (ICAT '92), Tokyo, Japan, pp. 178–182, 1992.

[3] J. Akita, T. Komatsu, K. Ito, T. Ono and M. Okamoto, "CyARM: Haptic sensing device for spatial localization on basis of exploration by arms," *J. Advances in Human-Computer Interaction*, Vol. 2009, Article ID 901707, 6 pages, 2009.

[4] M.O. Alhalabi, V. Daniulaitis, H. Kawasaki and T. Hori, "Medical training simulation for palpation of subsurface tumor using HIRO," The First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (WHC'05), Pisa, Italy, pp. 623–624, March 2005.

[5] T. Amemiya, H. Ando, and T. Maeda, "Virtual force display: Direction guidance using asymmetric acceleration via periodic translational motion," The World Haptics Conference, pp. 619–622, 2005.

[6] T.Amemiya, H. Ando, T. Maeda, "Lead-Me Interface for a Pulling Sensation from Hand-held Devices." ACM Transactions on Applied Perception, Vol. 5, No 3, Article no 15, 2008.

[7] T. Amemiya, H. Sugiyama, "Orienting kinesthetically: A haptic handheld wayfinder for people with visual impairments," ACM Transactions on Accessible Computing, Vol. 3, No 2, Article 6, 23 pages, 2010.

[8] W.A. Aviles, J.F. Ranta, "Haptic Interaction with Geoscientific Data," The Fourth PHANTOM Users Group Workshop, AI Lab Technical Report No. 1675 and RLE Technical Report No. 633, MIT, pp. 78–81, 1999.

[9] T. Barbieri, L. Mosca, L. Sbattella, "Haptic and aural graphs exploration for visually impaired users," The Conference and Workshop on Assistive Technologies for People with Vision and Hearing Impairments: Assistive Technology for All Ages (CVHI-2007), Spain, Vol. 415 of CEUR Workshop Proceedings, 2007.

[10] J. Barrio et al., "Report on WP3: CP3/4 with agreed specification input from WP4 and feasibility study on wearable sensing glove, hand posture identification, small-sized haptic display and flexible polymer actuator display," IST-2006-27141 IMMERSENSE, August 2006.

[11] M. Bergamasco, B. Allotta, L. Bosio, L. Ferretti, G. Perrini, G.M. Prisco, F. Salsedo, and G. Sartini, "An Arm Exoskeleton System for Teleoperation and Virtual Environment Applications," IEEE Int. Conference on Robotics and Automation (ICRA), Vol. 2, pp. 1449–1454, 1994.

[12] L. Biagiotti, G. Borghesan, C. Melchiorri, "A multimodal haptic mouse for visually impaired people," The 2nd Int. Conference on Enactive Interfaces (ENACTIVE-05), Genoa, Italy, 7 pages, November 2005.

[13] M. Bordegoni, G. Colombo, L. Formentini, "Haptic technologies for the conceptual and validation phases of product design," *Int. J. of systems and applications in computer graphics - Computers & Graphics*, Vol. 30, No 3, pp. 377–390, June 2006.

ISSN:2319-7900

[14] L. Buoguila, M. Ishii, M. Sato, "Scaleable SPIDAR: A Haptic Interface For Human-Scale Virtual Environments," First Int. Workshop Haptic Human Computer Interaction 2000 Glasgow, UK, August—September 2000, Springer LNCS 2058, pp. 182-193, 2001.

[15] M. Butler and P. Neave, "Object appreciation through haptic interaction," The 25th annual ASCILITE Conference of the Australasian Society for Computers in Learning in Tertiary Education: Hello! Where are you in the landscape of educational technology? (ASCILITE 2008), Melbourne, Australia, pp. 133-141, November - December 2008.

[16] C. Cadoz, and J-L. Florense, Fondement d'une démarche de recherche informatique/musique. *Revue d'Acoustique*, Vol. 1978, No 45, pp. 86–101, 1978.

[17] C. Cadoz, A. Luciani, J-L. Florens, N. Castagné, "ACROE–ICA Artistic Creation and Computer Interactive Multisensory Simulation Force Feedback Gesture Transducers," The Conference on New Interfaces for Musical Expression (NIME-03), Montreal, Canada, pp. 235-246, 2003.

[18] G. Campion, Qi Wang, V. Hayward, "The Pantograph Mk-II: a haptic instrument," IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS-2005), pp. 193–198, Edmonton, Alberta, Canada. August 2005.

[19] S. Cardin, D. Thalmann, and F. Vexo, "Wearable obstacle detection system for visually impaired people," VR workshop on haptic and tactile perception of deformable objects, pp. 50–55. Hannover, Germany, 2005.

[20] C.R. Carignan and D.L. Akin, "Using Robots for Astronaut Training," *Control Systems Magazine*, *IEEE*, Vol. 23, No 2, pp. 46–59, April 2003.

[21] G. Casiez, P. Plénacoste, Ch. Chaillou, and B. Semail, "The DigiHaptic, a New Three Degrees of Freedom Multi-finger Haptic Device," Virtual Reality International Conference, pp. 35-39, May 2003.

[22] A. Chang, J. Gouldstone, J. Zigelbaum, H. Ishii, "Pragmatic haptics," TEI'08, ACM, pp. 251–254, 2008.

[23] R. Chemuturi, F. Amirabdollahian, K. Dautenhahn, "Adaptive training algorithm for robot-assisted upper-arm rehabilitation, applicable to individualised and therapeutic human-robot interaction," *Journal of Neuroengineering and Rehabilitation*, Vol. 10, No 102, September 2013.

[24] E. Chinellato, M. Antonelli, B.J. Grzyb, A.P. del Pobil, "Implicit Sensorimotor Mapping of the Peripersonal Space by Gazing and Reaching," *J. IEEE Trans. on Autonomous Mental Development archive*, Vol. 3, No 1, pp. 43–53, March 2011.

[25] F. Chinello, M. Malvezzi, C. Pacchierotti and D. Prattichizzo, "A three DoFs wearable tactile display for exploration and manipulation of virtual objects," IEEE Haptics Symposium (HAPTICS), pp. 71–76, 2012.

[26] Y. Coello and O. Iwanow, "Effect of structuring the workspace on cognitive and sensorimotor distance estimation: no dissociation between perception and action," *Perception & Psychophysics*, Vol. 68, No 2, pp. 278–289, 2006.

[27] S. Comai and D. Mazza, "A Haptic-Enhanced System for Molecular Sensing," The 12th IFIP TC13 Conference on Human-Computer Interaction (INTERACT 2009), Uppsala, Sweden, LNCS, vol. 5727, pp 493–496, August 2009.

[28] O.A. Daud, "Haptic Systems for Post-Stroke Rehabilitation: from Virtual Reality to Remote Rehabilitation," PhD, University of Trento, Italy, Ch. 2, p. 17, 2011.

[29] N.B. Debats, I. Kingma, P.J. Beek, J.B.J. Smeets, "The Precision of "Haptic" Rod Length Perception Is Reduced by Lack of Visual Precision," EuroHaptics 2012, Springer-Verlag Berlin Heidelberg, Part II, LNCS 7283, pp. 19–24, 2012.

[30] D. DiFilippo and D.K. Pai, "The AHI: an audio and haptic interface for contact interactions," The 13th Annual ACM Symposium on User Interface Software and Technology (UIST), San Diego, California, USA, Vol. 2, No. 2, pp. 149–158, November 2000.

[31] L. Dominjon, J. Perret, A. Lécuyer, "Novel Devices and Interaction Techniques for Human-Scale Haptics," *Visual Computer*, Vol. 23, No. 4, pp. 257–266, March 2007.

[32] T. Endo, S. Tanimura, H. Kawasaki, "Development of a Surgical Knife Device for a Multi-Fngered Haptic Interface Robot," The 18th IFAC World Congress, Milano, Italy, pp. 6460–6465, Aug.– Sept. 2011.

[33] M.S. Erden, T. Tomiyama, "Human-intent detection and physically interactive control of a robot without force sensors," IEEE Transactions on Robotics, Vol. 26, No. 2, pp. 370–382, April 2010.

[34] H. Esen, A. Sachsenhauser, K. Yyano, M. Buss, "A multi-user virtual training system concept and objective assessment of trainings," 16th IEEE Int. Conference on Robot and Human Interactive Communication, Jeju, Korea, pp. 1084-1089, August 2007.

[35] G. Evreinov, T.V. Evreinova, R. Raisamo, "Method, Computer Program and Device for Interacting with a Computer," Finland Patent Application, WO2011061395 A1, May 2011.

[36] T.V. Evreinova, G. Evreinov, R. Raisamo, "Virtual sectioning and haptic exploration of the volumetric shapes in the absence of visual feedback," Advances

ISSN:2319-7900

in Human-Computer Interaction, Vol. 2013, article ID 740324, 15 pages. Hindawi, July 2013.

[37] T.V. Evreinova, G. Evreinov, R. Raisamo, "Evaluation of effectiveness of the StickGrip device for detecting the topographic heights on digital maps," Int. Journal of Computer Science and Application (IJCSA), Vol. 9, No. 3, pp. 61–76, 2012.

[38] T.G. Evreinova, G. Evreinov, R. Raisamo, "A Case Study on Non-Visual Pen-Based Interaction with the Numerical Data," *Int. Journal of Human Computer Interaction* (IJHCI), Vol. 4, No. 2, pp. 70–87, 2013.

[39] T.V. Evreinova, G. Evreinov, R. Raisamo, "An Evaluation of the virtual curvature with the StickGrip haptic device: a case study," *UAIS Journal*, Vol. 12, No. 2, pp. 161–173, 2013.

[40] T.V. Evreinova, G. Evreinov, R. Raisamo, "Estimating topographic heights with the StickGrip haptic device," Int. Symposium on Multimedia Applications and Processing (FedCSIS) Szczecin, Poland, pp. 691–697, September, 2011.

[41] T.V. Evreinova, G. Evreinov, R. Raisamo, "Haptic visualization of bathymetric data," Haptic Symposium (Haptics 2012), Vancouver, Canada, pp. 359–364, March 2012.

[42] T.V. Evreinova, G. Evreinov, R. Raisamo, "Interpretation of ambiguous images inspected by the STICKGRIP device," IADIS Interfaces and Human Computer Interaction (IADIS IHCI) Rome, Italy, pp. 209–217, July 2011.

[43] A. Favetto, E.P. Ambrosio, S. Appendino, A. Battezzato, F.C. Chen, D. Manfredi, M. Mousavi, F. Pescarmona, "Embedding an Exoskeleton Hand in the Astronaut's EVA Glove: Feasibility and Ideas," *Int. Journal of Aerospace Sciences*, Vol. 1, No. 4, pp. 68–76, 2012.

[44] I. Font, S. Weil, M. Franken, M. Steinbuch, L. Rovers, "Haptic feedback designs in teleoperation systems for minimal invasive surgery," IEEE Int. Conference on Systems, Man and Cybernetics, Vol. 3, pp. 2513–2518, 2004.

[45] M. Fritschi, M.O. Ernst, M. Buss, "Integration of kinesthetic and tactile display: a modular design concept," EuroHaptics International Conference (EH 2006), Paris, France, pp. 607–612, July 2006.

[46] D. Glesser, F. Berard, J.R. Cooperstock, "Overcoming limitations of the trackpad for 3D docking operations," CHI 2013: Changing Perspectives, Paris, France, pp. 1239-1244, April-May 2013.

[47] V. Gourishankar, G. Srimathveeravalli, T. Kesavadas, "HapStick: A high fidelity haptic simulation for billiards," The Second Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (WHC'07), Washington, DC, USA, Tsukuba, Japan, pp. 494-500, March 2007.

[48] D.A. Grahn, J.L. Dillon, H.C. Heller, "Heat Loss Through the Glabrous Skin Surfaces of Heavily Insulated, Heat-Stressed Individuals," *Journal of Biomechanical Engineering, ASME*, Vol. 131, Article ID 071005–1, July, 2009.

[49] A. Gupta and M.K. O'Malley, "Design of a Haptic Arm Exoskeleton for Training and Rehabilitation," IEEE/ASME Transactions on Mechatronics, Vol. 11, No. 3, pp. 280–289, June 2006.

[50] M. Hachet, A. Kulik, "Elastic Control for Navigation Tasks on Pen-based Handheld Computers," IEEE Symposium on 3D User Interfaces, (3DUI), pp. 91–96, March 2008.

[51] M. Hachet and A. Kulik, "Elastic control on mobile phones," retrieved http://youtu.be/WwlT-7lIZCY, May 30, 2014.

[52] HapticMaster, Commercially available system, retrieved http://www.vrlab.ctw.utwente.nl/eq/HapticMaster.html, May 30, 2014.

[53] O. Halabi and H. Kawasaki, "Five Fingers Haptic Interface Robot HIRO: Design, Rendering, and Applications." Advances in Haptics, Mehrdad Hosseini Zadeh (Ed.), InTech, pp. 221–240, 2010.

[54] B. Hammond, "A computer vision tangible user interface for mixed reality billiards," IEEE Int. Conference on Multimedia and Expo (ICME), Hannover, Germany, pp. 929–932, June 2008.

[55] C. Harding, I.A. Kakadiaris, J.F. Casey, R.B. Loftin, "A Multisensory System for the Investigation of Geoscientific Data," *Computers & Graphics*, Vol. 26, No. 2, pp. 259–269, 2002.

[56] V. Hayward, "Survey of Haptic Interface Research at McGill University," Workshop on Advances in Interactive Multimodal Telepresence Systems, Munich, Germany. Hieronymus Buchreproduktions GmbH, pp.91-98, March 2001.

[57] V. Hayward, O.R. Astley, M. Cruz-Hernandez, D. Grant, G. Robles-De-La-Torre, "Haptic Interfaces and Devices," Sensor Review, Vol. 24, No 1, 16-29, 2004.

[58] F. Hemmert, S. Hamann, M. Löwe, J. Zeipelt, G. Joost, "Weight-Shifting Mobiles: Two-Dimensional Gravitational Displays in Mobile Phones," The 28th Int. Conference on Human Factors in Computing Systems (CHI), Atlanta, GA, USA, pp. 3087–3091, April 2010.

[59] Y. Hirata, M. Sato, "3-Dimensional Interface Device for Virtual Work Space," IEEE/RSJ International Conference on IROS, Vol. 2, pp. 889–896, July 1992.

ISSN:2319-7900

[60] M. Hioki, H. Kawasaki, H. Sakaeda, Y. Nishimoto, and T. Mouri, “Finger rehabilitation support system using a multifingered haptic interface controlled by a surface electromyogram,” *Journal of Robotics*, Vol. 2011, Article ID 167516, 10 pages, October 2011.

[61] B. Horan, A. Bhatti, A. Nahavandi, “Method and apparatus for haptic control,” Patent application EP2422939B1, Deakin University, June 2013.

[62] INCA6D, Commercially available system, retrieved http://www.est-kl.com/products/haptic-feedback/haption/inca-6d.html, May 30, 2014.

[63] K. Ito, M. Okamoto, J. Akita, T. Ono, I. Gyobu, T. Takagi, T. Hoshi, Y. Mishima, “CyARM: an alternative aid device for blind persons,” International conference on Human Factors in Computing Systems (CHI), Portland, Oregon, USA, pp. 1483–1486, April 2005.

[64] G. Jansson and K. Billberger, “The PHANToM Used without Visual Guidance,” The First Phantom Users Research Symposium (PURS’99), Heidelberg, Germany, pp. 27-30, May 1999.

[65] G. Jansson, and K. Larsson, “Identification of haptic virtual objects with different degrees of complexity,” Eurohaptics, Edinburgh, UK, University of Edinburgh, pp. 57-60, July 2002.

[66] G. Jansson, M. Bergamasco, A. Frisoli, “A New Option for the Visually Impaired to Experience 3D Art at Museums: Manual Exploration of Virtual Copies,” *Visual Impairment Research*, Vol. 5, p. 1–12, 2003.

[67] A. Jarillo-Silva, O.A. Domınguez-Ramırez, V.́ Parra-Vega, P. Ordaz-Oliver, “PHANToM OMNI haptic device: kinematic and manipulability,” Electronics, Robotics and Automotive Mechanics Conference (CERMA), Cuernavaca, Mexico, pp. 193–198, September 2009.

[68] S. Kamuro, K. Minamizawa, N. Kawakami, S. Tachi, “Ungrounded kinesthetic pen for haptic interaction with virtual environments,” The 18th IEEE International Symposium Robot and Human Interactive Communication, (RO-MAN), Toyama, Japan, pp. 436– 441, Sept-Oct 2009.

[69] S. Kamuro, K. Minamizawa, S. Tachi, “An Ungrounded Pen-Shaped Kinesthetic Display: Device Construction and Applications,” IEEE World Haptics Conference (WHC), Istanbul, pp.557–562, June 2011.

[70] S. Kamuro, Y. Takeuchi, K. Minamizawa, S. Tachi, “Haptic Editor,” ACM SIGGAPH, Posters, Los Angeles, CA, USA. ACM, NY, USA. Article 14, 2012.

[71] K. Karunanayaka, S. Siriwardana, C. Edirisinghe, R. Nakatsu, P. Gopalakrishnakone, “Haptic mouse magnetic field based near surface haptic and pointing interface,” *Int. Journal of Interactive Digital Media*, Vol. 1, N. 2, pp. 8–15, July 2013,

[72] H. Kawasaki, “Multi-Fingered Haptic Interface Robot and Its Application Systems,” Solid State Phenomena, Vol. 144, pp 1-8, 2009. Trans Tech Publications, Materials Science and Engineering, Switzerland, 2009.

[73] H. Kawasaki, T. Mouri, M.O. Alhalabi, Y. Sugihashi, Y. Ohtuka, S. Ikenohata, et al, “Development of Five-Fingered Haptic Interface: HIRO-II,” The 15th Annual international conference on artificial reality and telexistence (ICAT '05), University of Canterbury, Christchurch, New Zealand, pp.209–214, December 2005.

[74] A.J. Kelley, S.E. Salcudean, “On the development of a force-feedback mouse and its integration into a graphical user interface,” *ASME Dynamic Systems and Control*, DSC Vol. 55-1, pp. 287–294, 1994.

[75] T.W. Kenyon, “Tactile control indicator,” US Patent 2,754,505, 1956.

[76] I. Kingma, R. Van de Langenberg, P.J. Beek, “Which mechanical invariants are associated with the perception of length and heaviness of a nonvisible handheld rod? testing the inertia tensor hypothesis,” *J. Exp. Psychol. Hum. Percept. Perform.* Vol. 30, No. 2, 346–354, 2004.

[77] Ki-Uk Kyung and Dong-Soo Kwon, “Tactile Displays with Parallel Mechanism,” Ch. 23, retrieved http://www.intechopen.com/books/parallel_manipulators_new_developments/tactile_displays_with_parallel_mechanism, May 30, 2014.

[78] B. Knörlein, G. Székely, M. Harders, “Visuo-haptic collaborative augmented reality ping-pong,” Int. Conference on Advances in Computer Entertainment technology (ACE'07), Salzburg, Austria, Vol. 203, pp. 91–94, June 2007.

[79] K.-U. Kyung, J.-Y. Lee, “Ubi-Pen: A Haptic Interface with Texture and Vibrotactile Display,” IEEE *Computer Graphics and Applications*, Vol. 29, No. 1, pp.24–32, Jan-Feb. 2009.

[80] K.-U. Kyung, H. Choi, D.-S. Kwon, S.-W. Son, “Interactive mouse systems providing haptic feedback during the exploration in virtual environment,” Computer and Information Sciences (ISCIS) LNCS Vol. 3280, pp 136–146, October 2004.

[81] K.-U. Kyung, J.-Y. Lee, “wUbi-Pen: windows graphical user interface interacting with haptic feedback stylus,” ACM SIGGRAPH, NY, USA, New Tech Demos, Article 42, 2008.

[82] K.-U. Kyung, J.-S. Park, “Ubi-Pen: Development of a Compact Tactile Display Module and Its Application to a Haptic Stylus,” The 2nd EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, Tsukaba, Japan, pp. 109–114, March 2007.

ISSN:2319-7900

[83] K.-U. Kyung and D.-S. Kwon, "Tactile Displays with Parallel Mechanism," Ch. 23 In Jee-Hwan Ryu (Ed.) Parallel Manipulators, New Developments, I-Tech Education and Publishing, Vienna, Austria, pp. 445–456, 2008.

[84] V. Lévesque, J. Pasquero, V. Hayward, "Display of Virtual Braille Dots by Lateral Skin Deformation: Feasibility Study," ACM Trans. on Applied Perception, Vol. 2, No. 2, pp. 132–149, 2005.

[85] L. Liu, S. Miyake, N. Maruyama, K. Akahane and M. Sato, "Development of Two-handed Multi-finger Haptic Interface SPIDAR-10," 9th Int. Conference, EuroHaptics 2014, Versailles, France, June 24-26, Springer, LNCS Vol. 8618-8619, 2014.

[86] I. Mack, S. Ferguson, K. McMenemy, S. Potts, and A. Dick, "Interactive force sensing feedback system for remote robotic laparoscopic surgery," J. Transactions Institute of Measurement and Control, Vol. 34, No. 4, pp. 376-387, January 2012.

[87] A. Mashayekhi, A. Nahvi, M. Yazdani, M. Moghadam, M. Arbabtafti, M. Norouzi, "VirSense: a novel haptic device with fixed-base motors and a gravity compensation system," *Industrial Robot: An International Journal*, Vol. 41, No. 1, pp. 37–49, 2014.

[88] T.H. Massie and J.K. Salisbury, "The PHANTOM Haptic Interface: A Device for Probing Virtual Objects," The ASME Winter Annual Meeting, Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. Chicago, IL, Vol. 1, pp. 295-301, November 1994.

[89] M. Memeo, C. Campus, L. Lucagrossi and L. Brayda, "Similarity of blind and sighted subjects when constructing maps with small-area tactile displays: performance, behavioral and subjective aspects," 9th Int. Conference, EuroHaptics 2014, Versailles, France, June 24-26, Springer, LNCS Vol. 8618-8619, 2014.

[90] R.L. McCormick, "Six degree of freedom miniature in VIVO robot for laparoendoscopic single-suite surgery," MSc. Thesis, University of Nebraska–Lincoln, 2011.

[91] H.C. Miles, S.R. Pop, S.J. Wattb, G.P. Lawrence, N.W. John, "A review of virtual environments for training in ball sports," *J. Computers & Graphics*, Vol. 36, No. 6, pp. 714–726, October 2012.

[92] K. Minamizawa, D. Prattichizzo, S. Tachi, "Simplified Design of Haptic Display by Extending One - point Kinesthetic Feedback to Multipoint Tactile Feedback," IEEE Haptics Symposium (Haptics'2010), Waltham, Massachusetts, USA, pp. 257–260, March, 2010.

[93] K. Minamizawa, S. Fukamachi, H. Kajimoto, N. Kawakami, S. Tachi, "Gravity Grabber: Wearable Haptic Display to present Virtual Mass Sensation," ACM SIGGRAPH, Emerging Technologies, San Diego, CA, USA, Vol. 1, pp. 250–258, August 2007.

[94] R. Mizuno, K. Ito, T. Ono, J. Akita, T. Komatsu, and M. Okamoto, "User's motion for shape perception using CyARM," The 5th Int. Conference on Foundations of Augmented Cognition, (FAC'09), Neuroergonomics and Operational Neuroscience: Held as Part of HCI International, San Diego, CA, USA, pp. 185–191, July 2009.

[95] A. Mohtat, C. Gallacher and J. Kovecses, "Developing Immersive Virtual Worlds through Realistic Contact Rendering and Improved Transparency," 9th Int. Conference, EuroHaptics 2014, Versailles, France, June 24-26, Springer, LNCS Vol. 8618-8619, 2014.

[96] D. Morris, Ch. Sewell, F. Barbagli, K. Salisbury, N.H. Blevins, and S. Girod, "Visuohaptic simulation of bone surgery for training and evaluation," IEEE *Computer Graphics and Applications*, Vol. 26, No. 6, pp. 48–57, November 2006.

[97] D. Naidu, R. Stopforth, G. Bright, and Sh. Davrajh, "A 7 DOF exoskeleton arm: shoulder, elbow, wrist and hand mechanism for assistance to upper limb disabled individuals," IEEE AFRICON 2011, pp. 1–6, Livingstone, Zambia, September 2011.

[98] M. Newcomb, C. Harding, "A Multi-modal interface for road planning tasks using vision, haptics and sound," The 2nd Int. Symposium on Visual Computing (ISVC), LNCS Vol. 4292, No. 2, pp. 417– 426, 2006.

[99] G. Nikolakis, D. Tzovaras, S. Moustakidis, M.G. Strintzis, "CyberGrasp and PHANTOM integration: enhanced haptic access for visually impaired users," The 9th Int. Conference "Speech and Computer" (SPECOM), St. Petersburg, Russia, September 2004 retrieved http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.408.4294&rep=rep1&type=pdf, July 2, 2014.

[100] OMEGA-3, Product information, retrieved http://www.forcedimension.com/products/omega-3/overview, July 2, 2014.

[101] A.U. Pehlivan, O. Celik, and M.K. O'Malley, "Mechanical design of a distal arm exoskeleton for stroke and spinal cord injury rehabilitation," IEEE 12th Int. Conference on Rehabilitation Robotics (ICORR), Zurich, Switzerland, pp. 1–5, June, 2011.

[102] J.C. Perry, J. Oblak, J.H. Jung, I. Cikajlo, "Variable structure pantograph mechanism with spring suspension system for comprehensive upper-limb haptic movement training," *Journal of Rehabilitation Re-*

ISSN:2319-7900

search and Development, Vol. 48, No. 4, pp. 317–333, 2011.

[103] Phantom Omni Device Guide, retrieved http://dl.geomagic.com/binaries/support/downloads/Sensable/3DS/Omni_Device_Guide.pdf, May 30, 2014.

[104] D. Prattichizzo, F. Chinello, C. Pacchierotti, K. Minamizawa, "RemoTouch:A System For Remote Touch Experience," The 19th IEEE Int. Symposium on Robot and Human Interactive Communication, (RO-MAN)Viareggio, Italy, pp. 676–679, Sept. 2010.

[105] D. Prattichizzo, F. Chinello, C. Pacchierotti, M. Malvezzi, "Towards wearability in fingertip haptics: A 3-DoF wearable device for cutaneous force feedback," IEEE Trans. on Haptics, Vol. 6, No. 4, pp. 506–516, Oct.-Dec. 2013.

[106] Quanser 3DOF, Commercially available system, retrieved http://www.quarcservice.com/ReleaseNotes/files/haptic_3dof_pantograph_cartesian_plant_block.html, May 30, 2014.

[107] Quanser 5DOF, Commercially available system, retrieved http://www.quarcservice.com/ReleaseNotes/files/quarc_using_devices_haptics.html, May 30, 2014.

[108] C. Ramstein, V. Hayward, "The Pantograph: a large workspace haptic device for a multi-modal human-computer interaction," Conference on Human Factors in Computing Systems (CHI'94), Boston, MA, USA, April 1994.

[109] J.M. Romano and K.J. Kuchenbecker, "The AirWand: Design and Characterization of a Large-Workspace Haptic Device," IEEE Int. Conference on Robotics and Automation, Kobe, Japan, pp. 1461–1466, May 2009.

[110] J.K. Salisbury, Jr., "Making graphics physically tangible," *Communications of the ACM*, Vol. 42, No. 8, pp. 74–81, 1999.

[111] G. Sankaranarayanan, H.I. King, S.-Y. Ko, M.J.H. Lum, D.C.W. Friedman, J. Rosen, and B. Hannaford, "Portable surgery master station for mobile robotic telesurgery," Int. Conference on Robot Communication and Coordination (Robocomm), Athens, Greece, Article No. 28, October 2007.

[112] E.J. Shahoian, K.M. Martin, B.M. Schena, D.F. Moore, Vibrotactile Haptic Feedback Devices. US Patent 8,169,402B2, May 2012.

[113] S. Sharmin, G. Evreinov, R. Raisamo, "Non-Visual Feedback Cues for Pen Computing," The First Joint Eurohaptics Conf. and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, WordHaptics, (WHC) Pisa, Italy, pp. 625–628, March 2005.

[114] B. Siciliano, O. Khatib, "Springer handbook of robotics," New York: Springer-Verlag NY Inc, pp. 719–725, 2008.

[115] M. Simonnet, S. Vieilledent and J. Tisseau, "Navigation performances of a blind sailor using a haptic and auditory cartographic system on board," The Eighth Int. Conference on Pervasive Computing. Helsinki, Finland, pp. 49–50, May 2010.

[116] A. Sledd, M.K. O'Malley, "Performance Enhancement of a Haptic Arm Exoskeleton," The 14th Int. Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, Arlington, VA, USA, pp. 375–381, March 2006.

[117] W. Snapp-Childs, E. Casserly, M. Mon-Williams, G.P. Bingham, "Active prospective control is required for effective sensorimotor learning," *PLOS ONE*, Vol. 8, No. 10, pp. 1-10, October 2013.

[118] M. Stamm, M.E. Altinsoy, S. Merchel, "Identification accuracy and efficiency of haptic virtual objects using force-feedback," The 3rd Int. Workshop on Perceptual Quality of System (PQS '10), 2010.

[119] L.J. Stocco, S.E. Salcudean, F., "Sassani Optimal kinematic design of a haptic pen," EEE/ASME Transactions on Mechatronics, Vol. 6, No. 3, pp. 210–220, September 2001.

[120] T.M. Sukal, M.D. Ellis, J.P.A. Dewald, "Shoulder abduction-induced reductions in reaching work area following hemiparetic stroke: neuroscientific implications," *Journal Experimental Brain Research*, Vol. 183, No. 2, pp. 215–223, November 2007.

[121] Y. Suzuki, M. Kobayashi, "Air Jet Driven Force Feedback in Virtual Reality," IEEE *Computer Graphics and Applications*, Vol. 25, No. 1, pp. 44–47, January 2005.

[122] C. Swindells, A. Unden, T. Sang, "TorqueBAR: An ungrounded haptic feedback device," The 5th Int. Conference on Multimodal Interfaces (ICMI), Vancouver, British Columbia, Canada, pp. 52–59, November 2003.

[123] H.Z. Tan, M.A. Srinivasan, C.M. Reed, N.I. Durlach "Discrimination and identification of finger joint-angle position using active motion," ACM Transactions on Applied Perception, Vol. 4, No. 2, pp. 1–14, July 2007.

[124] H.Z. Tan, W.M. Rabinowitz, "A new multi-finger tactual display," The 5th Int. Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, American Society of Mechanical Engineers Dynamic Systems and Control Division, Vol. 58, pp. 515–522, 1996.

[125] H.Z. Tan, N.I. Durlach, C.M. Reed, W.M. Rabinowitz, "Information transmission with a

ISSN:2319-7900

multifinger tactual display," *Perception & Psychophysics*, Vol. 61, No. 6, pp. 993-1008, August 1999.

[126] H.Z. Tan, C.M. Reed, N.I. Durlach, "Optimum Information Transfer Rates for Communication through Haptic and Other Sensory Modalities," IEEE Transactions on Haptics, Vol. 3, No. 2, pp. 98–108, April-June 2010.

[127] B. Tornil, N. Baptiste-Jessel, "Music haptic: musical harmony notions for all with a force feedback mouse and a spatial representation," The Int. Computer Music Conference, ICMC 2005 Free sound, pp. 439–442, September 2005.

[128] N.G. Tsagarakis, Y. Sarakoglou, D.G. Caldwell, "A combined haptic interface and its application on the pre-operative planning for total hip replacement," EuroHaptics 2004, Munich, Germany, pp. 348–351, June 2004.

[129] M.Y. Tsalamlal, N. Ouarti, M. Ammi, "Non-intrusive Haptic Interfaces: State-of-the Art Survey," In book Haptic and Audio Interaction Design. Ian Oakley I., Brewster S. (Eds.), LNCS 7989, Springer, pp. 1–9, 2013.

[130] M.Y. Tsalamlal, N. Ouarti, M. Ammi, "Psychophysical study of air jet based tactile stimulation," IEEE World Haptics Conference (WHC), Daejeon, Korea, pp. 639–644, April 2013.

[131] TULA35, Commercially available actuator, Specifications retrieved http://www.technohands.co.jp/en/products/um-tula.html, May 30, 2014.

[132] Twin-Pantograph Haptic Pen, retrieved http://www.ece.ubc.ca/~tims/twinelb.html, May 30, 2014.

[133] M. Ueberle, N. Mock, M. Buss, "ViSHaRD 10, a novel hyperredundant haptic interface," The 12th Int. Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, Chicago, IL, USA, pp. 58–65, March 2004.

[134] M. Ueberle, N. Mock, A. Peer, C. Michas, M. Buss, "Design and control concepts of a hyper redundant haptic interface for interaction with virtual environments," IEEE/RSJ Int. Conference on Intelligent Robots and Systems (IROS), Workshop on Touch and Haptics, Sendai, Japan, pp. 58–65, Sept.- Oct. 2004.

[135] M.-W. Ueberle, "Design, control, and evaluation of a family of kinesthetic haptic interfaces," Ph.D. Dissertation in Technischen Universität München at the Fakultät of Elektrotechnik und Informationstechnik, 2006.

[136] S. Ullrich, T. Kuhlen, "Haptic palpation for medical simulation in virtual environments," IEEE Transactions on visualization and computer graphics, Vol. 18, No. 4, pp. 617–625, April 2012.

[137] R.Q. Van der Linde, P. Lammertse, "HapticMaster–a generic force controlled robot for human interaction," *Industrial Robot: An International Journal*, Vol. 30, No. 6, pp.515–524, 2003.

[138] ViSHaRD10 Virtual Scenario Haptic Rendering Device, retrieved http://en.souvr.com/CaseStudy/201001/5766.html and http://cordis.europa.eu/result/brief/rcn/3980_en.html, May 30, 2014.

[139] S.P. Walker, J.K. Salisbury, "Large haptic topographic maps: MarsView and the proxy graph algorithm," SI3D ACM Symposium on Interactive 3D graphics, pp. 83–92, April 2003.

[140] Website: ACROE technology Retroactive Gestural Transducers, retrieved http://acroe.imag.fr/produits/TGR/technologie/technologie_en.html, May 30, 2014.

[141] Website: AirWand, retrieved http://haptics.seas.upenn.edu/index.php/Research/Projects, May 30, 2014.

[142] Website: ARCSLab: Adaptable, Relational and Cognitive Software Environments, AudioTact, retrieved http://arcslab.dei.polimi.it/?software=audiotact-and-l-math, May 30, 2014.

[143] Website: Buru-Navi. Haptic Illusions, retrieved http://www.brl.ntt.co.jp/people/t-amemiya/research.html or http://www.youtube.com/watch?feature=player_embedded&v=Yj_WnNWV8F4, May 30, 2014.

[144] Website: Chaillou C, Casiez G, Martinot F., Pan Q. Interagir dans des environnements 3D Interagir dans des environnements 3D Des solutions permettant d agir sur des objets virtuels 3D, retrieved http://slideplayer.fr/slide/459785/, May 30, 2014.

[145] Website: HapStick, retrieved http://www.vrlab.buffalo.edu/projects_haptics/hapstick/main.html, May 30, 2014.

[146] Website: HIRO-II, retrieved http://faculty.qu.edu.qa/ohalabi/Work/Research.html, May 30, 2014.

[147] Website: Kuntz, S. Virtual Reality Devices, Gravity Grabber 2009, retrieved http://cb.nowan.net/blog/category/vr/virtual-reality-devices/, May 30, 2014.

[148] Website: NextBigFuture, MAHI-EXO II, retrieved http://nextbigfuture.com/2012/09/brain-wave-reading-robot-exoskeleton.html, May 30, 2014.

[149] Website: O'Malley, M. Design and Development of a Cybernetic Exoskeleton for Hand-Wrist Rehabilitation, 2012, retrieved

ISSN:2319-7900

http://mahilab.rice.edu/content/design-and-development-cybernetic-exoskeleton-hand-wrist-rehabilitation, May 30, 2014.
[150] Website: Pantograph M1, retrieved http://www.personal.rdg.ac.uk/~shshawin/LN/L8hapticdesigns.html, May 30, 2014.
[151] Website: Pantograph medium, http://www.cim.mcgill.ca/~haptic/pictures/pantograph.mpg, retrieved May 30, 2014.
[152] Website: Pen-shaped kinesthetic display, retrieved May 30, 2014. http://www.ekouhou.net/%E5%8A%9B%E8%A6%9A%E6%8F%90%E7%A4%BA%E8%A3%85%E7%BD%AE/disp-A,2010-287221.html
[153] Website: Prattichizzo D., Human-centered robotics and haptics, 2012, retrieved http://prattichizzoblog.wordpress.com/2012/05/30/wearable-haptics-cutaneous-devices-skin-devices-cutaneous-kinesthetic-dissociation-sensory-subtraction-the-research-so-far-in-our-sirslab/, May 30, 2014.
[154] Website: Quanser serial robot, retrieved http://charm.stanford.edu/ME327/Xiyang, May 30, 2014.
[155] Website: Saiamu (サイアーム) The space recognition device, retrieved http://www.will-e.com/products/cyarm.html, May 30, 2014.
[156] Website: SIGGRAPH2008 News, retrieved http://news.mynavi.jp/photo/articles/2008/09/02/siggraph05/images/035l.jpg, May 30, 2014.
[157] Website: SPIDAR, retrieved http://www.rrv.ro/trima/infrastructure/infrastructure/pages/spidar.htm and http://xavier.lepaul.free.fr/machins/inria/rapport/node20.html, May 30, 2014.
[158] Website: Vibrating pen, retrieved http://www.sis.uta.fi/~csgrev/NIT_2003/NIT2003.htm, May 30, 2014.
[159] Website: Withana (2010), Presentation retrieved http://vimeo.com/16765630, May 30, 2014.
[160] Welding and brash-painting, retrieved http://lasa.epfl.ch/skillassist/Background.dwt, May 30, 2014.
[161] M.M. Wickham, "A study of haptic interactions with an under actuated robot in three dimensions," MSc. Thesis, Iowa State University, Ames, Iowa, 2010.
[162] Wikipedia, Pantograph, retrieved http://en.wikipedia.org/wiki/Pantograph, May 30, 2014.
[163] A. Withana, M. Kondo, Y. Makino, G. Kakehi, M. Sugimoto, M., "ImpAct: Immersive haptic stylus to enable direct touch and manipulation for surface computing," Computers in Entertainment (CIE)-Special Issue: *Advances in Computer Entertainment Technology*, Archive, Vol. 8, No. 2, Article No. 9, December 2010.
[164] Z. Xu, R. Fiebrink, Y. Matsuoka, "Virtual Therapist: A Phantom robot-based haptic system for rersonalized post-surgery finger rehabilitation," IEEE Int. Conference on Robotics and Biomimetics (ROBIO), Guangzhou, China, pp. 1662–1667, December 2012.
[165] T. Yamamoto and K. Hirota, "Device for Estimation of Weight and Material of Contents by Shaking," 9th Int. Conference, EuroHaptics 2014, Versailles, France, June 24-26, Springer, LNCS Vol. 8618-8619, 2014.
[166] Y. Yang, Y. Zhang, "A New Cable-driven Haptic Device for Integrating Kinesthetic and Cutaneous Display," In: J.S. Dai, M. Zoppi and X. Kong (eds), ASME/IFToMM Int. Conference on Reconfigurable Mechanisms and Robots (ReMAR), King's College London, UK, pp.386–391, June 2009.
[167] Y. Yang, Y. Zhang, B. Lemaire-Semail and X. Dai, "Enhancing the simulation of boundaries by coupling tactile and kinesthetic feedback," 9th Int. Conference, EuroHaptics 2014, Versailles, France, June 24-26, Springer, LNCS Vol. 8618-8619, 2014.
[168] M. Ziat, I. Frissen, G. Campion, V. Hayward, C. Guastavino, "Plucked String Stiffness Affects Loudness Perception," In: I. Oakley and S. Brewster (Eds.): HAID, LNCS 7989, pp. 79–88, April 2013.

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